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Advanced Technology Direction and Control Communications Systems

Final Report

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DCPA Work Unit 2214G

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This report reflects The MITRE Corporation's research in appropriate advanced communications technologies for distributed, survivable direction and control systems for civil defense in the 1980's. In addition to network design options that have a near-term payoff, several potential technologies are described which may have a longer-term payoff. These systems are communications satellites, meteor scatter burst communications, JTIDS and Packet Radio, and SCULPT, a spread spectrum satellite system. In addition, digital transmission, switching and distribution are described because of their application by the commercial communications services in the 1980's.

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July 1979

For: Defense Civil Preparedness Agency
Washington, D.C.

By: Frederick W. Leuppert and
James D. Morrell

DCPA Contract: DCPA-01-78-C-0259
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DCPA Review Notice
This report has been reviewed in the Defense Civil Preparedness Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Defense Civil Preparedness Agency.

EXECUTIVE SUMMARY

The purpose of this study is to research appropriate advanced technologies and present concepts and initial designs for distributed, survivable direction and control (D&C) communications systems for civil defense in the 1980's.

Although the existing communications networks are adequate for benign conditions, they are not expected to be sufficiently flexible and survivable under stress. Population relocation operations and changes in civil defense locations and responsibilities cannot be accommodated. The present commercial telephone network cannot be relied upon because restoration after almost assured damage is dependent upon a manual process. The present HF radio backup network (CDNARS) has insufficient capacity and therefore cannot meet the anticipated needs.

Conceptual design of a responsive communication system must await consideration of Program D-prime and the establishment of FEMA, as well as detailed tradeoff analyses of the various design options in performance, cost, risk and development time. For the near term, implementation of distributed, switched AT&T Long Lines network options and saturation routing strategies can provide a relatively quick payoff. In the longer term, the design of redundant modes of communication is the key to survivability. An automatically restored AT&T Long Lines system, embodying digital switching and saturation routing is visualized as the basic system. In addition, an independent satellite network should be implemented, perhaps in the millimeter wavelengths, with TDMA and DAMA capabilities. A third capability, operationally similar to the military MEECN* system, is justified for communications system survivability. For this purpose, a meteor burst scatter communications system seems to provide the requisite characteristics. This scheme uses successive meteor trails to reflect radio energy and permit direct point-to-point communication over distances of up to 1500 kilometers. This medium appears to be survivable in a nuclear environment, and a low probability of intercept and anti-jam capability are enhanced due to the directional character of the specular meteor trail reflections.

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*Minimum Essential Emergency Communications Network

At state and local levels, JTIDS/Packet Radio can augment existing police, fire and land line communications. Both systems permit data to be distributed to a large number of users. They are line-of-sight systems and use relays for coverage beyond the horizon. Both technologies are mobile and survivable. For information feedback and radiation sensor transmissions an automatic system such as SCULPT** appears to have potential. SCULPT offers privacy of communications, some immunity to interference and the ability to accommodate various users with different data rates. All would use the same bandwidth either simultaneously or alternately at random without need for network discipline. The random access capability with a low duty cycle could result in a capability to accommodate a large number of users.

A more detailed system definition study is a natural follow-on to this preliminary overview.

**SCULPT: Satellite communications using low power technique. A spread spectrum system being developed by The MITRE Corporation for the Maritime Commission.

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1.0 INTRODUCTION

1.1 Purpose and Scope

The purpose of this study is to research appropriate advanced technologies and discuss concepts and initial designs for distributed, survivable, direction and control systems for civil defense in the 1980's.

Civil defense direction and control (D&C) systems are analogous to military command and control systems. They both involve resources that permit executives to exercise D&C, and both include the communications resources to support the execution of D&C functions. D&C systems support the interaction of the federal, state and local levels of the governmental hierarchy before, during and after overt enemy action and involve alerting, emergency information and feedback operations.

The primary focus of this study is on advanced technologies for the communications subsystem. The communications subsystem binds together the various elements of the D&C process and hence, the effectiveness of the D&C system is related to the performance of the communications subsystem.

The approach of this study is to identify the operational and technical requirements of the D&C system and then describe advanced communications technologies which are applicable to these requirements. This study:

- Discusses the requirements for a civil defense direction and control communications system;
- Identifies and describes advanced technologies for the D&C communications role; and
- Evaluates initial design concepts employing advanced technologies.

1.2 Background

According to the contractual Statement of Work for this project, a D&C system embraces:

- Facilities, personnel and systems, with necessary procedures to permit civil government executives at all levels to exercise effective direction and control of operations in crisis evacuation, trans-attack, in-shelter, and post-shelter periods, including but not limited to operations to keep to a minimum the radiation dose burden of survivors;

- Survivable systems to provide both alerting and attack warning to the civilian population, to local and state officials and to federal civilian and military authorities;

- Survivable systems to provide emergency information and advice to the sheltered population through the trans-attack, in-shelter and post-shelter periods; and

- Survivable systems to obtain, report, and analyze information on attack effects of all types, as the basis for the conduct of necessary emergency operations.

D&C activity nodes are the Defense Civil Preparedness Agency headquarters in Washington, D.C., and its relocation site, eight regional offices, the state civil preparedness agencies and many local civil defense activities. The eight regional offices, most of which are in hardened sites, are located at: Maynard, Massachusetts; Olney, Maryland; Thomasville, Georgia; Battle Creek, Michigan; Denton, Texas; Denver, Colorado; Santa Rosa, California; and Bothell, Washington. The eight regions are shown in Figure 1. The hardened sites have the potential for sustained operations under crisis conditions for thirty days.

The National Warning System (NAWAS) is the federal portion of the nationwide civil defense warning system. It consists of leased voice "party line" circuits for dissemination of warnings to state governments and selected political subdivisions. Civil defense warnings

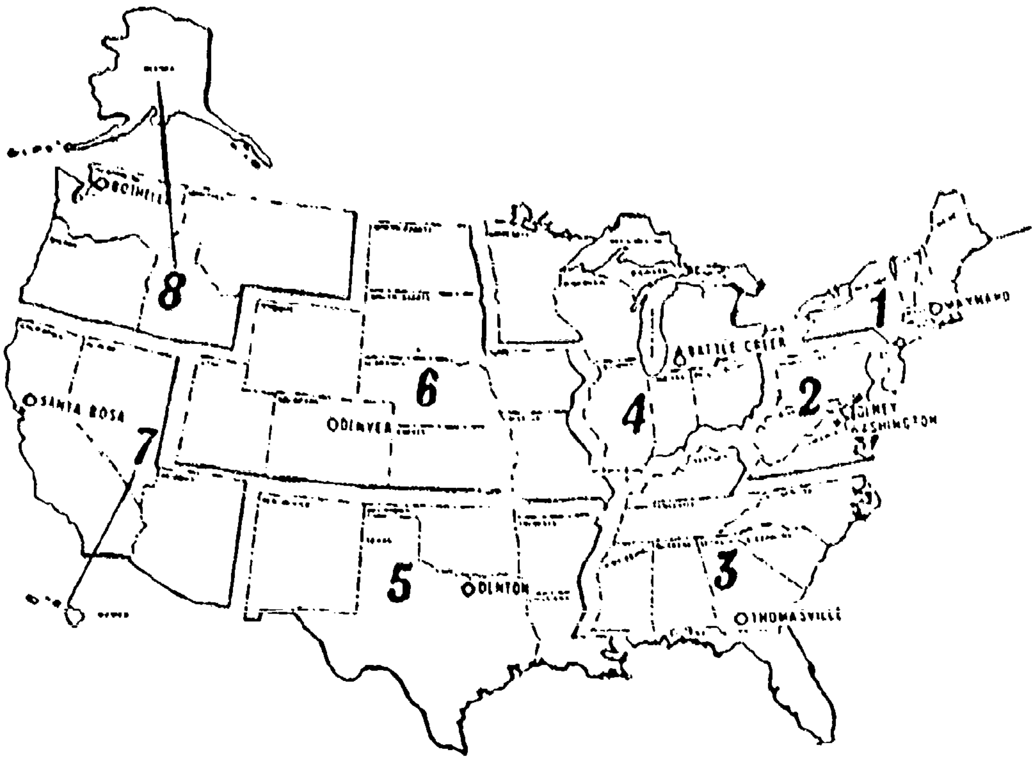


FIGURE 1
DCPA REGIONS

originate at the National Civil Defense Warning Center collocated with NORAD at Colorado Springs or from a designated alternate warning center. The leased circuits connect the primary and alternate warning centers to the DCPA headquarters, the eight regional centers, 346 federal agencies and more than 1400 local warning points which are manned twenty-four hours a day. The NAWAS has a total of more than 2300 terminals dispersed throughout the 49 continental states.

The DCPA is also responsible for a special warning system for the Washington, D.C., area. The Washington Warning System, WAWAS, consists of: a siren system; a wireline system connecting local Washington and suburban civil defense, military, and other selected federal activities; and a bell and light warning system in certain federal buildings. Procedures and equipment are also available to broadcast warnings over local commercial radio stations.

Three communications nets provide the bulk of the emergency information services. The Civil Defense National Teletype System (CDNATS) is the primary record* network linking the DCPA headquarters, the relocation headquarters, the eight regional centers, the 50 states, Puerto Rico, the District of Columbia, and certain locations in Canada. The CDNATS accepts and processes messages simultaneously from all of its teletype circuits. An automatic switching feature allows users to send messages to a single address or to a multiple of addresses within the system. The CDNATS is a leased, dedicated, full-period, full-duplex, store and forward, 100-word per minute

*i.e., a communications system that provides a textual record of the communications handled by the system.

teletype system. State terminals are multiplexed* at their respective region. The message switches at Regions Two and Six are interconnected by a full-duplex 2400 baud circuit.** The layout of the National Civil Defense Teletype System is shown in Figure 2.

The Civil Defense National Voice System (CDNAVS) is a combination of Automatic Voice Network (AUTOVON) circuits and dedicated, full-time, leased wire line circuits. AUTOVON is used between DCPA headquarters, the relocation headquarters and the regional offices, thereby providing these offices with access to all AUTOVON users in the continental United States. Circuit pre-emption is provided at the DCPA national and regional offices. The full-time dedicated circuits provide direct connections between each of the regional offices and the state offices in its region. Hardened cables have been installed in the vicinity of a number of regional centers. The Civil Defense National Voice System is shown in Figure 3.

The Civil Defense National Radio System (CDNARS) is a high frequency radio network used as backup to the CDNATS and CDNAVS. The system is operational in 49 states, the CDPA headquarters and relocation headquarters, the eight regional offices, the District of Columbia, Puerto Rico, and the Canal Zone. The CDNARS is comprised of a national net which consists of the net control station at Region Two (Olney, Maryland), seven regional offices, and the relocation site; and a group of eight nets between regional

*Multiplexing refers to any technique which permits more than one signal to share one physical communications facility.

**Speed in bauds is equal to the number of signaling elements or symbols per second.

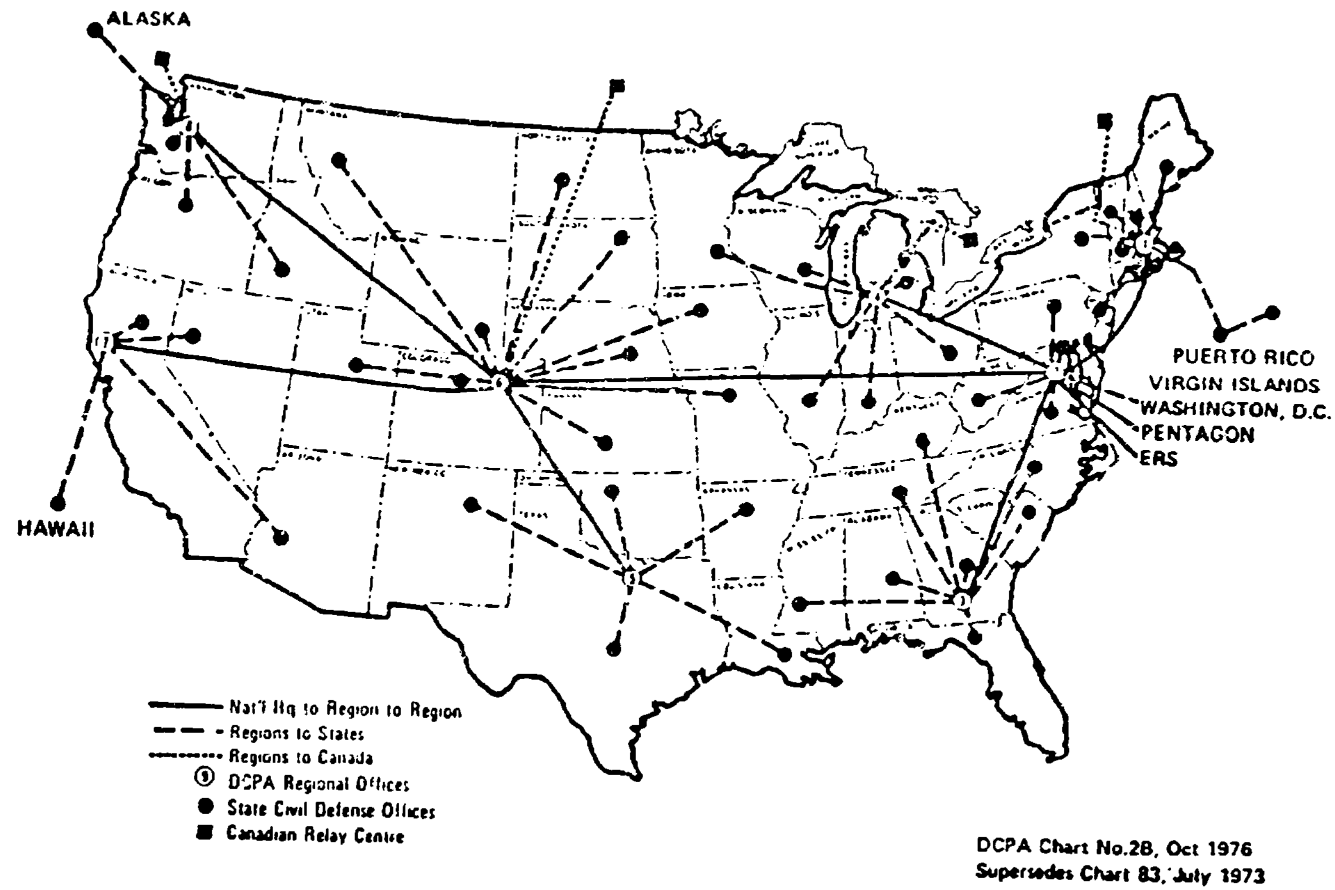


FIGURE 2
CIVIL DEFENSE NATIONAL TELETYPE SYSTEM

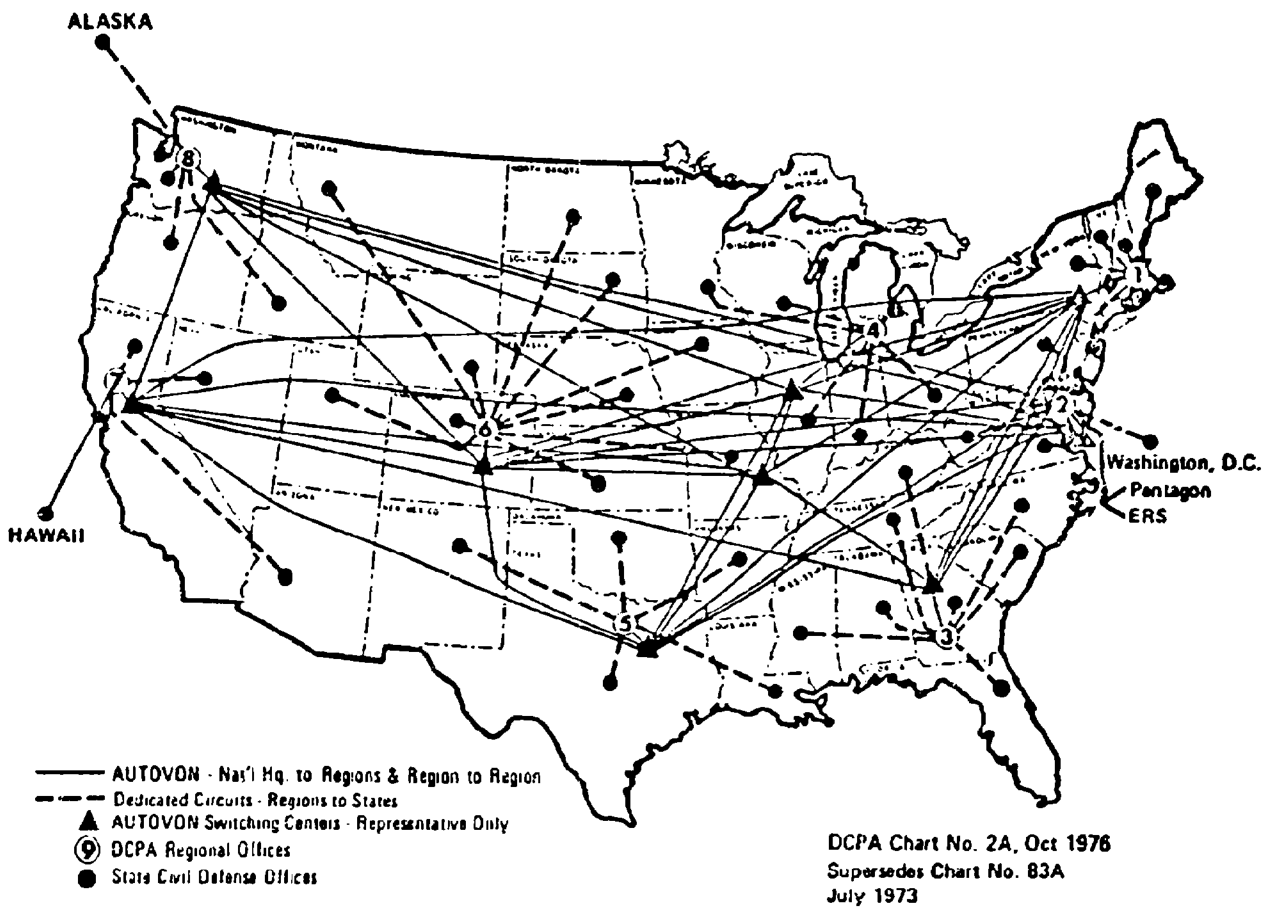


FIGURE 3
CIVIL DEFENSE NATIONAL VOICE SYSTEM

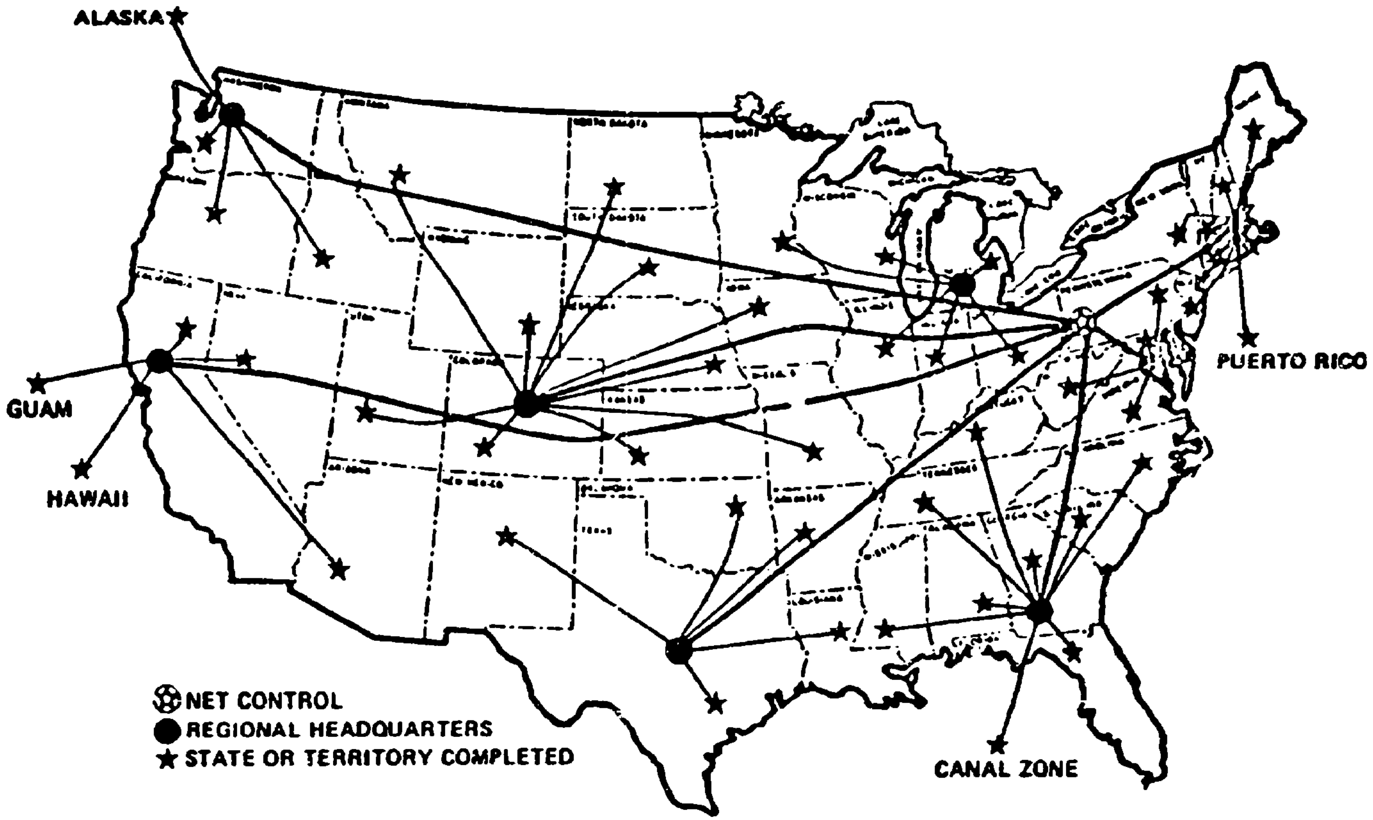
and state levels, with the federal regional centers acting as net control stations. The Civil Defense National Radio System is shown in Figure 4.

The DCPA has one other dedicated D&C communications system. The Decision Information Distribution System (DIDS), partially established but now mothballed, was designed to use a 50 kw low frequency station to broadcast warnings, actuate sirens, and turn on warning receivers throughout the 48 contiguous states. It was to operate 24 hours a day, transmitting time checks and weather broadcasts on a frequency of 179 KHz. The DCPA plan was to have ten low frequency DIDS stations and two very low frequency stations on approximately 50 KHz, broadcasting coded signal transmissions. The DIDS was never activated.

By Executive Order 10952 and DoD Directive 5105.43, the DCPA is also required to develop plans and operate systems to undertake a nationwide post-attack assessment of the nature and extent of the damage resulting from enemy attack, and to identify surviving resources. Both direct, on-site assessment and reporting of damage and indirect assessment is used. Indirect damage assessment is achieved by calculations based on the type, size, and location of nuclear detonations and their proximity to facilities and resources, and the vulnerability of the resources.

1.3 The Threat

The concept of DCPA activities for the 1980 timeframe is embodied in a program called D-prime. The worst-case threat of D-prime visualizes a major nuclear attack against U.S. population and industrial centers; it is in that context that the evaluation of advanced communications technologies is accomplished.



DCPA Chart No.21, Oct 1976
Supersedes Chart No.84
July 1973

FIGURE 4
CIVIL DEFENSE NATIONAL RADIO SYSTEM

2.0 D&C COMMUNICATIONS SYSTEM REQUIREMENTS - 1985

2.1 General

DCPA has the mission by public law* to "make appropriate provision for necessary civil defense communications and for dissemination of warning of enemy attacks to the civilian population." In addition, communications support must be provided for radiological monitoring/reporting, damage assessment and population relocation. It is beyond the scope of this study to determine what this broad charter will mean in terms of quantitative communications requirements in the 1985 time period and beyond. Implementation of the D-prime program (Section 1.3) and integration of needs of related services within the new Federal Emergency Management Agency (FEMA) with those of DCPA provide uncertainties that suggest a separate effort be undertaken to permit an overall, top-level system design. For the purposes of selecting and exploring candidate technologies that might have application to DCPA problems (the intent of this study), it is deemed sufficient to assume that the general character of the present needs will not change from the perspective of the user.

2.2 Existing D&C System

The existing D&C system from the user's viewpoint is synthesized into a form depicted in Figure 5. Basically, the architecture is one of two federal centers (one primary and a secondary) communicating with eight regional centers. These, in turn, communicate with state and then local governments. At present the communications services between federal centers and regions is not great - typically 6 voice

*Public Law 920, Federal Civil Defense Act (as amended), 81st Congress, 1948.

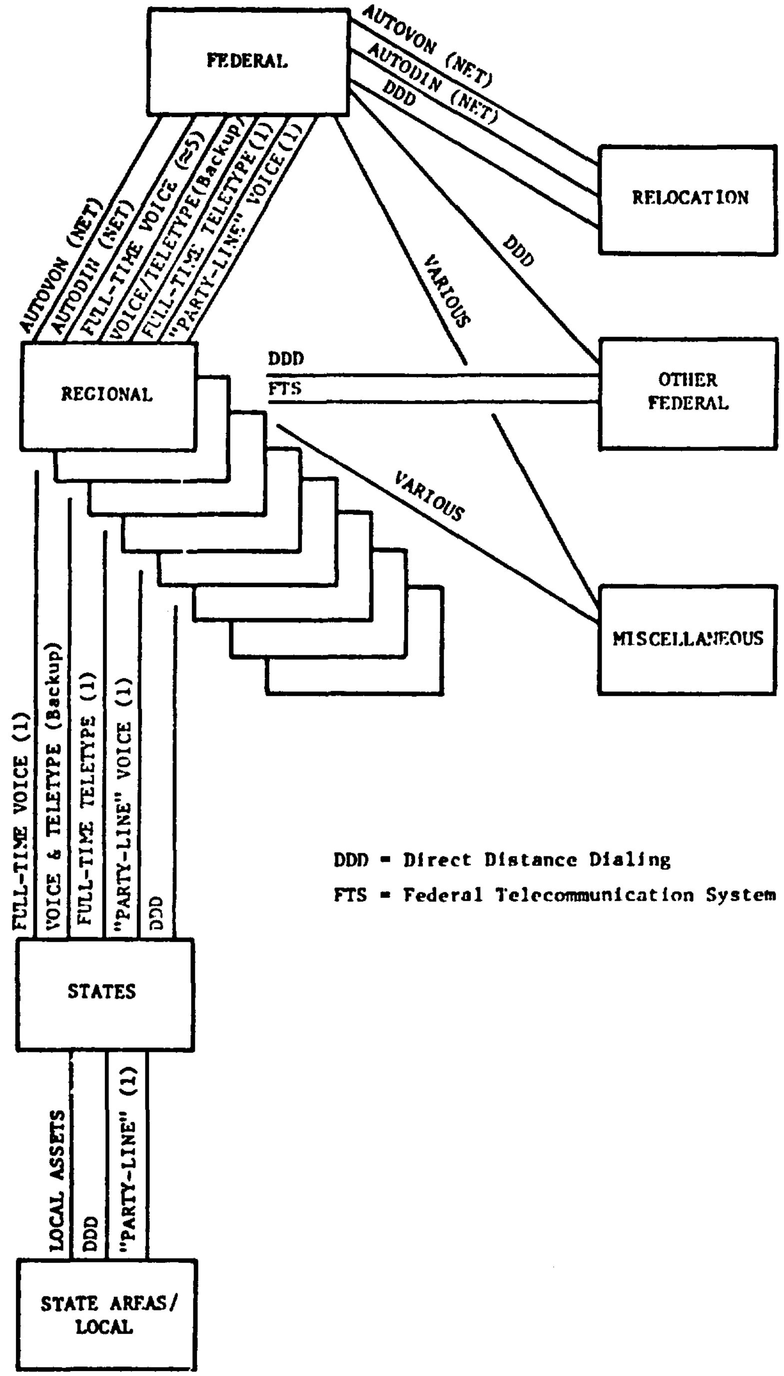


FIGURE 5
CURRENT D&C SYSTEM SCHEME

lines plus 1 teletype circuit. One voice line is "party-line", the others direct (full-time), two way circuits. In addition, the federal and regional centers have access to the Department of Defense AUTOVON and AUTODIN networks within the Continental United States. The dedicated voice and teletype lines, and AUTOVON/AUTODIN within the contiguous states, are carried by the AT&T Long Lines facilities. The backup for these channels is the HF radio system, CDNARS, which provides one voice and one teletype circuit. The federal and regional centers have access to the commercial Direct Distance Dialing (DDD) network. The regional centers can also use the Federal Telecommunications System (FTS), leased from the AT&T Long Lines system.

Communications channels between regional centers and primary state civil defense locations are even fewer in number and consist of two voice channels (one of which is "party-line"), one teletype circuit, and DDD access. All these lines are handled over AT&T Long Lines facilities. The HF radio backup of one voice and one teletype circuit extends to every state except Vermont.

Between the state centers and local civil defense activities only the single "party-line" voice circuit, supplemented by the DDD, exists. Both are carried by the commercial telephone system. In addition, local communications, such as police and emergency radios, are used.

In the event that region to state communications are disturbed, there is no quick-reaction alternative except to rely on DDD or the HF system, the CDNARS. If the communications outage is caused by destruction of a regional center, the adjacent regional center

absorbs the states in that sector and attempts to establish communications via DDD or CDNARS. If one or more state centers are neutralized, adjacent states try to adjust in the same manner.

Typical communications ranges are: from federal centers to regional centers, from line-of-sight to 5000 km; from regional centers to state centers, up to 1000 km (except Hawaii and Alaska, about 5000 km); state to local communications ranges seldom exceed 750 km. The 2400 baud circuit connecting Regions Two and Six is about 3000 km long.

2.3 Projected Requirements

Two of the basic determinants of civil defense communications needs will not vary significantly over the next decade or so. These determinants are: the nature of the civil defense threat, which determines the quantity and density of traffic, and the geographic distribution of civil defense agencies. Since there are no traffic projections or expression of communications needs other than those identified in 2.2 above, it is postulated that the requirement for future communications support is reflected by the current D&C communications system. Experience has shown, however, that actual requirements vary from projected requirements. In order to accommodate for this possibility, it is assumed that the actual volume of D&C communications in the 1980's may vary from today's volume by a factor of two. Based on the foregoing, the channel requirements for D&C communications in the 1980's would be:

- Between federal levels and regional centers:
    - Ten direct full-time voice channels
    - Two "party-line" channels
    - Two channels for teletype or facsimile
    - Two voice and two teletype/facsimile channels as backup
    - AUTODIN-I, AUTOVON and DDD switched networks

- Between regional centers and states:
  - Two full-time voice channels
  - Two "party-line" voice channels
  - Two teletype/facsimile channels
  - Two voice and two teletype/facsimile channels as backup
  - DDD switched network
- Between states and local agencies:
  - Two "party-line" voice channels
  - Local assets
  - DDD switched network

Additional changes in communications requirements will be induced by new programs such as full implementation of Program D-prime and the integration of DCPA into the Federal Emergency Management Agency (FEMA). The exact extent of the impact of these programs will not be known until the programs mature further. Program D-prime introduces the concept of massive population relocation, which requires a capability for mobile/transportation D&C communications. The degree of mobility and the required capacity of the mobile communications system is, at this time, open to conjecture. Likewise, the counterpart communications systems of other agencies comprising FEMA (Federal Disaster Assistance Administration, Federal Preparedness Agency, United States Fire Administration, Federal Insurance Agency) may be capable of either augmenting DCPA's D&C communications systems or placing additional demands upon it. At this time, the full impact of these programs is not clear.

3.0 ADVANCED COMMUNICATIONS TECHNOLOGIES

3.1 General

Because of the lead time required for the development of communications systems, the operating D&C system of the 1985 time frame will probably use technologies now known. This section of the project report describes a selection of advanced technologies that may be applicable to DCPA communications needs, and forms the basis for the discussion of D&C system concepts and designs in the next section of the report.

The two basic media for communications are radio and cable. The first two subsections briefly summarize advances in technology affecting these media. Digital communications technology is briefly described in the next subsection. A fourth discusses the application of communications satellites and the remainder deal with other subjects having a bearing on D&C communications.

3.2 Advances in Radio Communications

Radio communications, one of the two basic transmission mediums, is used extensively in the current D&C system. The Civil Defense National Radio System (CDNARS) uses high frequency radio transmissions. In addition, the leased teletype and voice systems, CDNATS and CDNAVS, include links operating in the microwave bands. The CDNARS capitalizes on the ionospheric reflection and atmospheric scattering characteristics of high frequency transmissions to provide extensive coverage. The microwave links, both terrestrial and satellite, are directional and limited to line-of-sight (usually about 50 kilometers for the non-satellite links).

The normal line-of-sight range of microwave radios can be extended by scattering microwave energy through the troposphere or reflecting microwaves off ionized meteor trails. Although tropospheric scatter is hardly a new technology, there are a number of on-going programs to develop tropospheric scatter for military applications similar to the D&C requirements. A MITRE paper, WP-21839, "An alternative Approach to Low Vulnerability Communications," dated June 1978, describes low vulnerability troposcatter communication between centers up to 150 km.

Meteor scatter uses long trails of ionized particles, formed by meteors entering the earth's atmosphere, to reflect microwave signals. Stored data can be forwarded at very high speed during brief bursts corresponding to the lifetimes of the individual meteor trails. Only those trails suitably oriented are used for point-to-point communications. As a consequence, transmission cannot be continuous. Nevertheless, the bandwidth of a single meteor scatter channel appears to be sufficiently large to support fairly high volume average data transmission rates.

The altitude of the reflecting meteor trails permits direct point-to-point communications over distances of up to 1500 kilometers and the propagation mechanism appears to be generally survivable in a nuclear environment. Because of these characteristics, meteor scatter appears to provide a unique capability for D&C communications. This technology is described in greater detail later in this report.

In addition to the range of microwave signals, frequency allocation and congestion are major problems in radio communications. The frequencies between 30 to 1000 MHz are the most congested because these are the frequencies used by broadcast, television, and mobile services. A solution to the congestion problem is to extend the portion of the spectrum used into the range above 1000 MHz.

At millimeter wavelengths, bandwidth is large but transmissions suffer severe attenuation in rain and snow, limiting the distance between stations. A significant advantage is that at these higher frequencies, a smaller antenna is needed.

Above 10 GHz to about 36 GHz (K band) bandwidth is high and congestion is not a problem, transmissions, however, are heavily attentuated in rain and, in some cases, even by clear atmosphere. At even higher frequencies such as those of light and infrared emissions, transmissions can be sharply focused reducing electromagnetic interference problems, but fog and precipitation may absorb the signal.

Satellite communications are transmitted in the higher UHF frequencies, the SHF band and the lower EHF frequencies.* The lowest frequency allocated for general communications via geostationary satellites is 2.5 GHz. Most allocations of frequencies below 2.5 GHz are for special purposes such as command channels to the satellites and for military applications. Frequencies in the lower part of the UHF spectrum have the advantages of relative efficiency and lower cost. The military uses UHF satellites for tactical communications where bandwidth is not critical.

The most important satellite frequencies today are in the 4/6 GHz band. Growth in satellite communications will be in the 12/14 GHz band with possibly further growth in the 20/30 GHz and 100 GHz bands.

The employment of LF and VLF frequencies has been considered for both civil defense and military communications in the past. In 1962,

*Radio frequency bands are designated as follows: VLF (very low frequency), 3-30 KHz; LF (low frequency), 30-300 KHz; MF (medium frequency), 300-3000 KHz; HF (high frequency), 3-30 MHz; VHF (very high frequency), 30-300 MHz; UHF (ultra high frequency), 300-3000 MHz; SHF (super high frequency), 3-30 GHz; EHF (extra high frequency), 30-300 GHz.

The MITRE Corporation prepared a survey of unconventional communications techniques for the Office of Civil Defense (see Bibliography, Attridge) which, addressed among others, a survivable VLF communications system. The study concluded that such a system would require antenna development and associated research before effective transmission is realized. The cost of a normal above-ground station is expensive and constructing a buried (hardened) system would magnify the cost. Since there is little evidence of recent advances in LF/VLF technology, this portion of the spectrum is not addressed further in this study.

Each band of the radio spectrum has its own unique characteristics and advantages/disadvantages in the D&C support role. Survivability requirements are more easily met as frequency increases and the effects of scintillation* and ionization** are minimized. Flexibility decreases as frequency increases and transmissions become limited to line-of-sight, but this characteristic can be accommodated by satellite-borne transponders or repeaters.

The radio medium is inherently more flexible than cable or wire, and relatively independent of fixed facilities. The supportability of radio communications is enhanced by the need to restore only the terminal nodes and not links also - except if a satellite relay is neutralized. Scatter techniques also mitigate the problems associated with the relay of line-of-sight transmissions.

3.3 Advances in Cables and Waveguides

Cables and waveguides offer several distinct advantages in the D&C application. They have an inherent tolerance to jamming,

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*Scintillation - random fluctuation or fading of a received signal, with the deviation being relatively small and usually quite rapid.

**Ionization - the formation of ions by the addition of electrons to the atmosphere by reaction to nuclear radiation.

interference, and eavesdropping. They have a very high capacity, far exceeding D&C requirements, which enhances channel availability for alternate circuit routing. The survivability of the DCPA communications network is enhanced by the pervasiveness and redundancy provided by the density of wire and cable which provide alternate routing around physical damage. Some hardening of the links is provided by burying the cables, both cross-country and in urban conduits. A measure of flexibility is provided by modern switching techniques which are discussed later in this report.

Coaxial cables, the highest capacity cables in commercial networks today, consist of a copper cylinder surrounding a single wire conductor. The bandwidth of early coaxial cables was up to 3 MHz but today is about 70 MHz, and two cables can carry 10,800 voice channels.

Waveguides are metal tubes in which very high frequency radio waves travel. Circular waveguides, "pipes" about two inches in diameter, are commonly called millimeter waveguides because they transmit frequencies from 40 to 110 GHz, which have a greater bandwidth than all the through-the-air transmissions together. Repeaters are placed every 30 to 40 kilometers on a waveguide, compared with two kilometers on large coaxial systems.

One of the newest technologies in cable communications is optical fiber cables, which use glass fibers with signals at or close to the frequencies of light. By removing all the impurities and making the glass of a high silica content, fibers with a very low transmission loss have been manufactured. Fibers with a loss of less than one decibel per kilometer have been developed, compared with losses as high as 28 decibels per kilometer in some conventional cables. Digital repeaters on fiberoptic cables with one decibel loss per kilometer can be more than ten kilometers apart.

Glass fibers can transmit either light or laser beams. Early experimental systems used light-emitting diodes (LEDs) as a source; as the current supplying the LED is modulated, the light emitted varies. For long distance, high capacity communications, however, the laser shows more promise than the LED.

A laser produces a narrow beam of light that is coherent (all the waves travel in unison) and is sharply monochromatic. In the telecommunications role, lasers provide highly controllable beams of great intensity which can be amplified, and which have a frequency 100,000 times higher than today's microwave signals. The potential information carrying capacity is therefore thousands of times greater than that of microwaves.

Laser signals can be multiplexed within a glass fiber; both frequency and time division multiplexing have been accomplished. Lasers can be made to emit at different frequencies by varying the semiconductor composition. Different frequency laser beams can be modulated separately and transmitted through the same fiber. A laser can be made to produce a series of narrow pulses of light, which can be applied to time division muitiplexing. Pulse trains can be used for pulse code modulation. Because the pulses are relatively far apart there is time to modulate them, and because the pulses are very narrow, several pulse trains can be interleaved (time division multiplexed).

The development of optical fiber systems represents the advanced technology area for the cable medium. Frequency allocation, coverage, and local use density present no significant problems to cable systems, but they are still vulnerable to physical interruption and destruction.

3.4 Advances in Transmission Technology

Historically, long distance transmission has been by analog means; the current D&C communications network is primarily an analog network. Virtually all long-haul communications transmission facilities are in the process of conversion to a digital form in order to achieve better performance at lower cost and also to be more compatible with the emerging use of encryption devices. Costs are reduced using the economies associated with solid-state devices which are primarily digital by nature. A major advantage of digital techniques for transmission is the regenerative process. In analog transmission, noise and distortion are amplified with the information signal at each repeater and soon the cumulative distortion and noise level becomes excessive. In digital transmission each repeater regenerates the digital signal, but does not repeat the distortion or noise.

Other advantages of digital systems are: (a) lower cost per voice channel, (b) greater utilization of the existing telephone plant, (c) all types of signals of interest to DCPA may be multiplexed without interference (voice, teletype, facsimile, data, video), and (d) much higher transmission rates may be achieved, thereby enhancing responsiveness. A disadvantage of digital transmission is that it uses a greater bandwidth to transmit messages at a given rate than an analog system would require.

The commercial communications networks today use pulse code modulation (PCM)* to encode voice digitally. With a requirement of 64,000 bits per second (bps) in each direction, PCM sampling 8,000 times per second can reproduce any frequency up to 4,000 Hz. Good quality speech, however, can be reproduced with 32,000 bps or less using fewer bits per sample.

*See Appendix.

Digital switching is another advanced technology that will be found in the commercial network in the 1980s. Circuit-switching and packet-switching are two high speed switching techniques. Circuit-switching requires that all switches between terminals are correctly connected before the transmission is made. Packet-switching is a form of store-and-forward switching designed primarily for computer-to-computer traffic. Time-division switching is practical when time-division multiplexing is used for digital signals. Time-division switching can handle streams of traffic of differing speeds, which will allow switching of voice, data, facsimile, and video.

PCM lines, digital radio, waveguides, satellite links, and other high capacity channels can be shared by many users by time-division. If, in addition, there are multiple access points to the channel, Time-Division Multiple Access or TDMA techniques may be employed. TDMA would be particularly useful where many customers would use the same channel, as in CDNAVS and NAWAS. Demand assignment of channels, DAMA, is being used experimentally. Multiple access is essential for efficient use of satellites supporting many ground stations.

An important point in digital communications is that this form of transmission greatly increases the capacity and responsiveness of the communications network. The magnitude of the increase greatly exceeds DCPA requirements in almost every regard, and therefore the point is not how well digital technology meets D&C requirements, but how well DCPA can exploit digital technology to better perform its mission. A detailed discussion of digital and pulse code communications is in the Appendix.

3.5 Communications Satellites

Communications satellites are components of many modern communications systems. For D&C, communications satellites make possible major advances within these areas:

- Use of higher radio frequencies
- Utilization of smaller ground station configurations
- Multiple beams
- Demand assigned multiple access (DAMA) techniques
- Digital techniques
- Burst transmissions
- Lasers

Like terrestrial microwave systems, satellite systems use different frequencies for reception and transmission. The frequencies used are generally expressed as pairs such as 4/6 GHz, 12/14 GHz, 20/30 GHz, with the first number referring to the frequency of the down-link and the second number referring to the up-link. Most currently operational communications satellites use UHF and SHF (microwave) frequencies, mainly in the 4/6 GHz band.

Initially the 4/6 GHz band for satellite communications was used because ground microwave technology already developed for this band could be quickly applied to satellite communications. However, the severe disadvantage of frequency interference between terrestrial and satellite microwave systems has encouraged use of the 12/14 GHz band for communications satellites.

In addition to reducing the interference in space and ground systems, the 12/14 GHz band has these advantages: the beam width is half that for a 4/6 GHz satellite, hence, twice as many satellites can be used without interference; the down-link beam can be narrower, with a resulting stronger signal and less expensive terminal equipment; multiple spot beams are possible, allowing reuse of frequencies; and more powerful satellites can be used, reducing ground station costs.

The disadvantage of the 12/14 GHz band is that rain, clouds, and fog attenuate the signal and introduce noise, particularly in tropical storms. The attenuation may be compensated for by the stronger signal in most but not all cases. Alternatively, two ground stations 15-25 km apart may be linked to receive the same signal, with the best signal of the two being used.

There are other bands for communications satellites higher in the spectrum which provide greater bandwidth. Experiments are being conducted at 20/30 GHz but more development work is needed. Operational systems in the 20/30 GHz band are not foreseen for the 1985 time frame.

Another important consideration is reduction of the size and cost of the communications ground station. Among the factors that could lower ground station costs are: a smaller, fixed antenna, application of demand assignment techniques, and mass production. There is also a tradeoff between maximizing satellite throughput and minimizing ground station costs. As a generalization, a given satellite transponder may handle a large number of channels or a large bandwidth at high ground station cost, or a small number of channels or small bandwidth at low ground station cost.

An advantage of going to higher frequencies is that smaller antennas can provide the same gain. A 20 meter antenna at 4/6 GHz, a 9 meter antenna at 12/14 GHz, and a 4 meter antenna in the 20/30 GHz band provide about the same gain.

A means of sharing satellite capacity among geographically scattered users is employment of multiple spot beams from the satellite and use of some capability to switch between beams. Each beam covers several hundred miles of earth, enough to support services similar to common carrier terrestrial communications systems. There

is a liability, however, in locating the switching equipment on the satellite at the risk of an unrepairable failure in space. This liability could be avoided by using demand-assigned multiple access (DAMA) techniques, which allow the communications satellite transponder capacity to be shared by many geographically scattered locations in accordance with variations in traffic demands. The sharing permits connection between any two ground stations without satellite-borne switching.

Like simple multiplexing, demand assignment can be achieved by frequency division, time division, or space division. Frequency division multiple access (FDMA) and time division multiple access techniques (TDMA) are most often used.

Digital techniques have replaced analog transmissions in satellite communications because more channels can be derived. Furthermore, digital transmission yields itself to the digital multiplexing techniques that use DAMA equipment.

The attenuation of electromagnetic waves in the atmosphere tends to increase with frequency, however, there are windows of reduced attenuation which could be used for satellite transmission. The carbon dioxide laser transmits at the frequency of one of these windows in the infrared region of the spectrum. The employment of lasers will extend the useful role of satellites but much work is needed to resolve practical problems.

In the 4/6 GHz band, satellites must be kept 3000 km apart to prevent signals transmitted to one satellite from interfering with another. Satellites using laser up-links can be very close together without interference. Lasers operate at frequencies more than 10,000

times higher than today's up-links, and hence have a much higher potential bandwidth. However, they may not be used on down-links because of possible dangers to persons on earth.

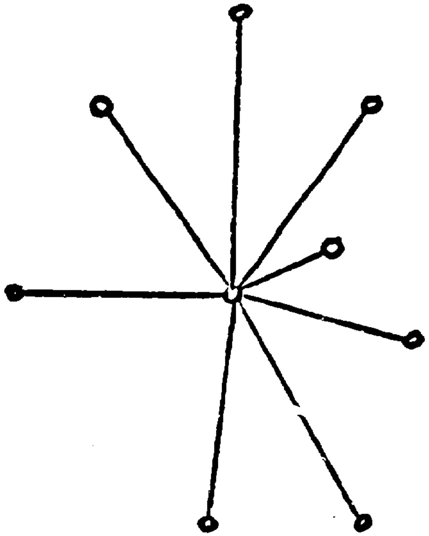
In summary, communications satellites have great potential in the technological development of higher frequency spectrum utilization, modest ground station requirements, and utilization of digital, DAMA/TDMA concepts. In combination with other technologies described in this report, communications satellites provide transmission capabilities which could improve D&C communications capabilities in the 1980s.

3.6 Network Design Options

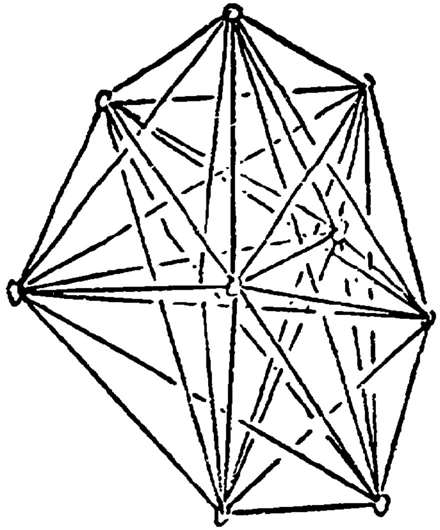
In the development of a survivable communications system, major consideration must be given to the routing, switching, and relaying of D&C traffic. Although the possibilities for interconnecting a large number of civil defense locations may, at first glance, appear so large as to be nearly limitless, all factor into the two basic configurations illustrated in Figure 6 (a) and (b), a star or grid.

In the star configuration, every node is connected to every other node through a single switch. Such a configuration provides connection between every pair of nodes with the fewest number of links. However, reliance on the availability of a single node and the absence of alternate routes essentially reduces the survivability of the entire network to the survivability of a single node.

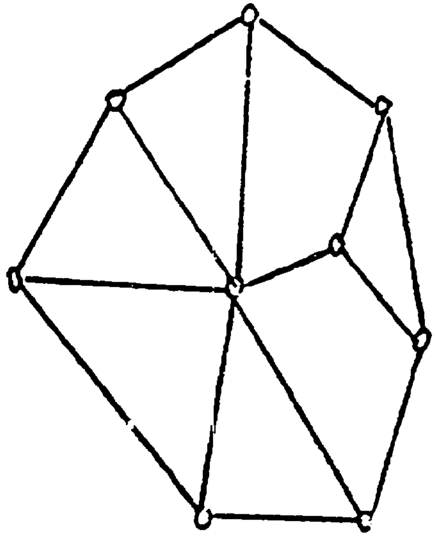
In comparison, the grid configuration achieves survivability by employing the maximum number of routes to connect every node to every other node directly (such a network is termed a clique). For a large number of nodes, the network cost to establish direct communications between all node pairs is usually unacceptably high.



(a) STAR



(b) GRID



(c) DISTRIBUTED GRID

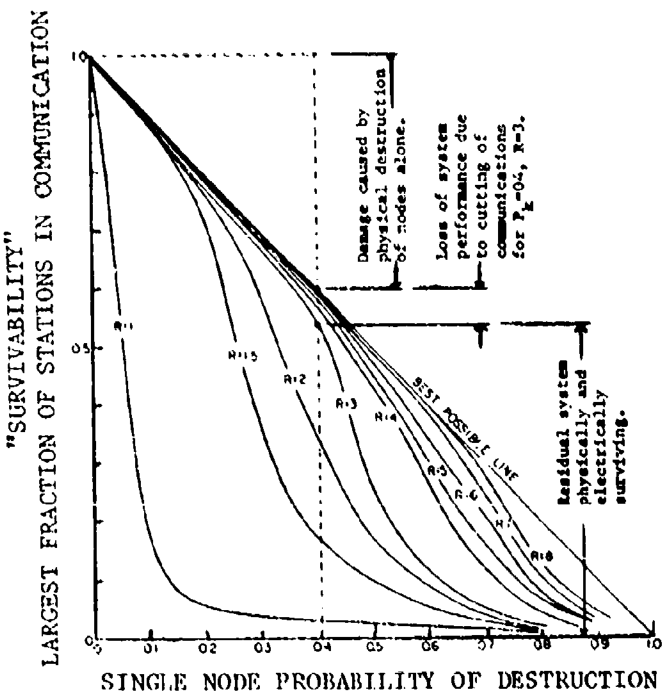
FIGURE 6
BASIC TOPOLOGICAL CONFIGURATIONS

In practice, to ensure survivability without excessive cost, a mixture of star and grid configurations is often used. This hybrid is a set of stars connected in the form of a larger star with an additional link forming a loop. This configuration is sometimes called "decentralized" because complete reliance upon a single node is not required.

Since the destruction of a small number of nodes can seriously disrupt or destroy communications even in a decentralized star, network configurations which achieve survivability through multiple routing without the excessive cost of a clique are of interest. Such networks are said to be distributed. An example of a distributed network is the grid illustrated in Figure 6 (c). Note that every node is connected to at least two others. Because multiple routes exist between all node pairs, requirements for grade-of-service, reliability, and survivability in individual links can often be relaxed with not appreciable degradation in network performance.

The survivability of networks depends upon the manner in which nodes are connected, the threat and the node/link "hardness" (the capability to withstand inflicted damage). The potential for survivability may be presented graphically as "draw-down" curves which show the degradation of some network performance measure resulting from an increased attack level, decreased node survivability, or other factor.

For example, the draw-down curve resulting from a worse case attack against a distributed network configured as an 18 x 18 node array is presented in Figure 7. The network performance measure ("survivability") is the percentage of nodes not physically destroyed and remaining in communication with the largest single group of



Source: Baran, 1966.

FIGURE 7
SENSITIVITY TO NODE DESTRUCTION

surviving nodes. The R-parameter associated with the different curves refers to "redundancy" level and is a measure of the capability for alternate message routing within the network.* Two key points are to be noticed in the figure. First, extremely survivable networks can be built using a moderately low redundancy of connectivity. Redundancy levels on the order of only three permit the withstanding of extremely heavy levels of attack with negligible loss to communications. Second, the survivability curves have sharp break points. A network will withstand an increasing attack level until a certain point is reached, beyond which the network rapidly deteriorates. Thus, the optimum degree of redundancy can be chosen as a function of the expected level of attack.

In comparison, Figure 8 shows the results for the case in which the nodes themselves survive and only the connecting links fail. Note that even when only half of the links are working there is little system degradation.

The worst case is the composite effect of failures of both the links and the nodes. Figure 9 shows the effects of link failures upon a network having 40 percent of its nodes destroyed. It is clear that with sufficient path redundancy, "unreliable" links can be used in a distributed network almost as effectively as perfectly reliable links.

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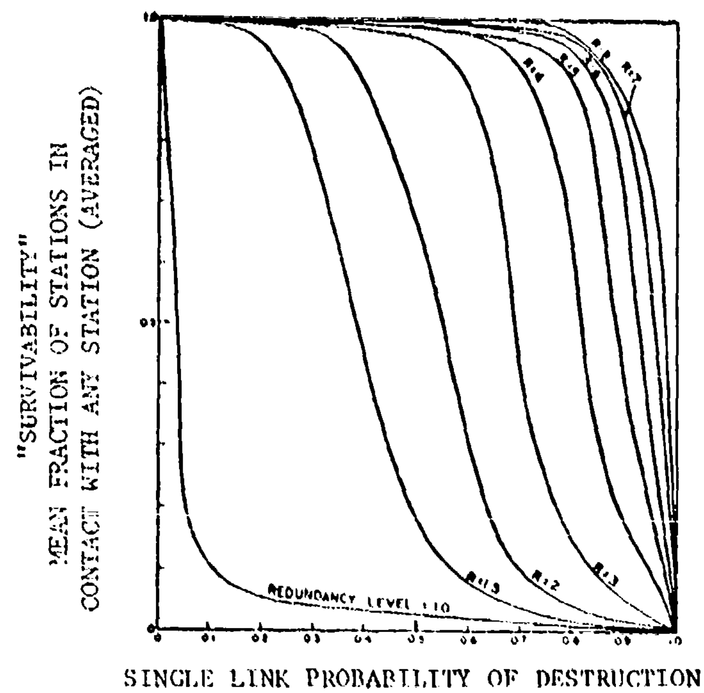
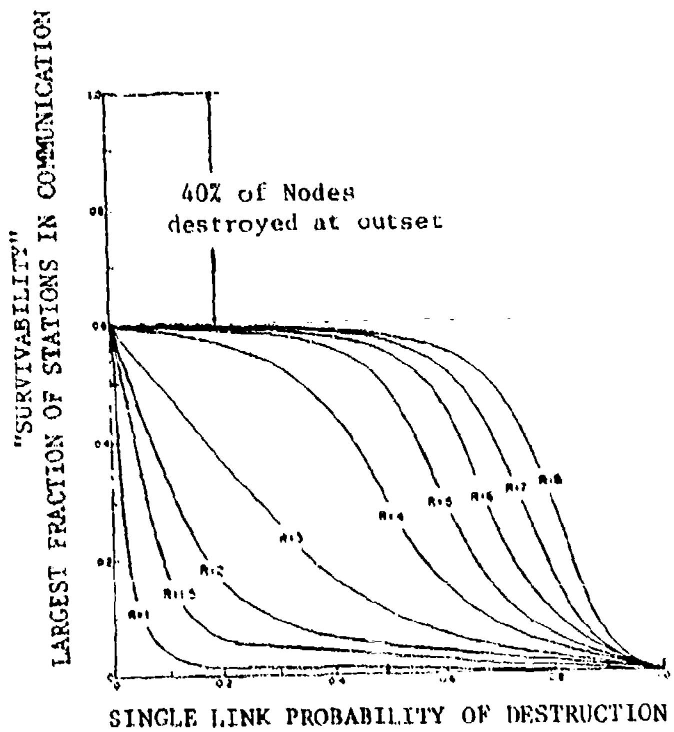
*A minimum span network, one formed with the smallest number of links possible is chosen as the reference point and is called "a network of redundancy level one." If two times as many links are used, the network is said to have a redundancy level of two, etc.



Source: Baran, 1966.

FIGURE 8
SENSITIVITY TO LINK DESTRUCTION



Source: Baran, 1966.

FIGURE 9
SENSITIVITY TO NODE AND LINK DESTRUCTION

In addition to providing alternate routes in the event of a disaster, circuit switching provides the potential to improve the grade-of-service and reduce cost. Improvements in grade-of-service relate to reduction in the call blocking probability, i.e., the probability that all circuits directed to an adjacent node are busy. For a given grade-of-service, the larger the trunk group the more efficient it will be in terms of occupancy. Therefore, the switching function should be introduced to concentrate circuits to improve network efficiency and reduce cost.

To illustrate the point, consider the nodal configuration of Figure 10. Assume that the interconnection plan requires every local office in Region A to connect with every local office in Region B. Under Plan I every local office in Region A is connected with every local office in Region B by a multiplicity of direct trunk groups. Under Plan II, regional switching centers have been established to connect Region A with Region B by a single trunk group. Assume further that the offered inter-office traffic is 0.5 Erlangs.* Under Plan I, the traffic offered to each trunk is 0.5 Erlangs; under Plan II, due to concentration by the switch, the traffic offered to the local-office trunk is 2.5 Erlangs and to the inter-region trunk 12.5 Erlangs. According to telephone traffic theory, the total number of long-distance trunk circuits required under Plan I to ensure a blocking probability of 3 percent is 3 x 5 x 5 or 75. Only 21 long-distance trunk circuits

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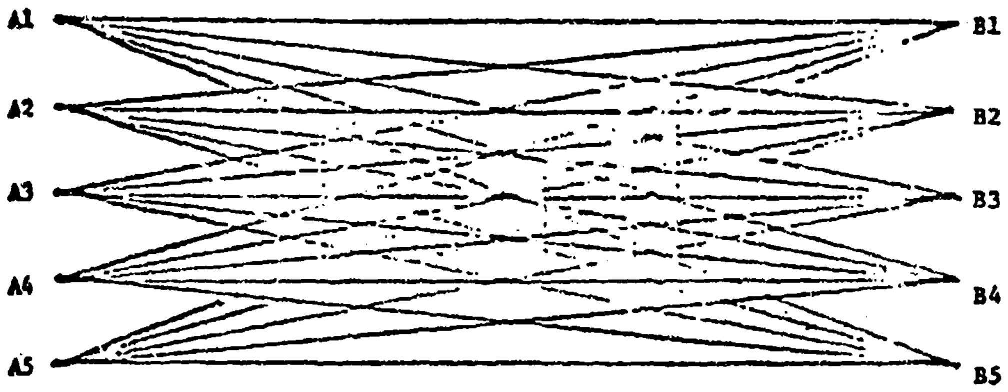
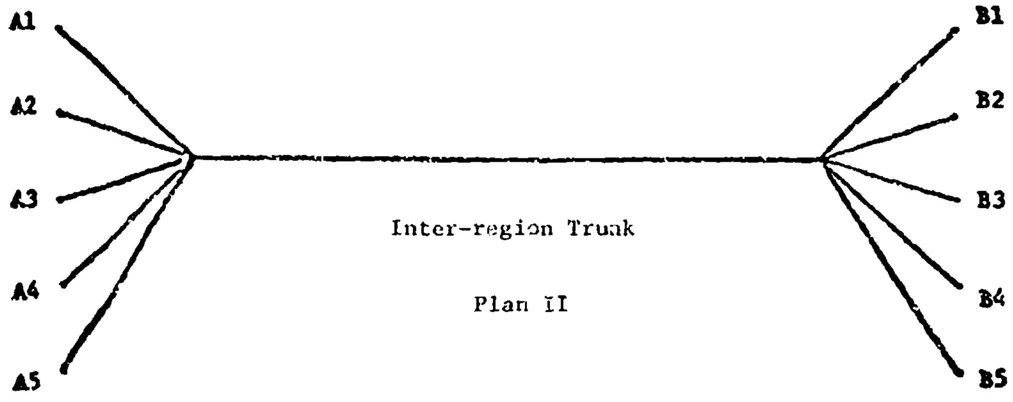
*The traffic offered is usually measured in Erlangs. An Erlang is equal to the amount of traffic one trunk can handle in one hour if it were occupied 100 percent of the time. The number of Erlangs is determined from the following formula:

Erlang = No. of Calls per Hour x Average Holding Time per Call (in hours).



Plan I



Plan II

FIGURE 10
SWITCHING EFFICIENCY EXAMPLE

would be required under Plan II. Thus, the introduction of switches at the regional centers leads to a requirement for only a 21-circuit trunk under Plan II rather than the twenty-five 3-circuit trunks required under Plan I. As a result of the greater efficiency realized by the larger trunk group, the number of long-distance, inter-regional circuit trunk miles could be reduced by a factor of nearly 3.6.

Intimately connected with the survivability and efficiency of a distributed network is the so-called routing algorithm. This algorithm describes the logic whereby messages are routed from source to destination even if the connectivity of the network has been radically modified by attack or other disaster.

A routing strategy can be completely described by a routing table and a call-control rule. A number of call-control rules presently used in various communications networks are:

- Originating Office Control

  Alternative choices are permitted only at the originating node and not at any tandem nodes. If at any successive node the prescribed choice is not available, the originating office is informed of this condition and an alternate route emanating from the originating node is attempted.

- Originating Office Control with Spill-Forward

  This is similar to originating office control except that control of the routing may be delegated to, or spilled-forward to, a successive node.

- Successive Office Control

  Each node is permitted to choose alternate routes solely on the basis of its own routing table.

The routing requirements for a D&C system are somewhat different from those of commercial telephone systems:

- Routing must remain effective even after the connectivity of the network has been modified by an attack or natural disaster.

- Routing must remain effective even under conditions of traffic overload.

- Subscriber switch (node) affiliations may change rapidly, and some subscribers are preemptable.

A routing strategy responsive to these requirements must necessarily be adaptive and, further, must satisfy system requirements for survivability and efficiency. Survivability considerations rule out techniques involving centralized control of the routing strategy, as performance is too dependent upon the survival of the control center. Therefore, techniques in which routing and adaption are controlled at each individual node must be considered. Such techniques are consistent with the call-control strategies described previously.

Adaptive routing strategies satisfying the above requirements fall into two classes:

- "Hot-potato" strategies which minimize delivery time, and

- Saturation routing which requires each node to relay the message to all adjacent nodes.

In the "hot-potato" adaptive strategies, routing is accomplished by storing in a small computer at each node a table of the current estimate of the time required to reach each possible destination when starting out along each link leaving the node.

In saturation routing, the originating switch stores the call identity in its search-in-progress table and sets an "originating call attempt timer." The message is then relayed sequentially to all adjacent nodes. The adjacent nodes receive message and examine their search-in-progress tables. If the call is not found in the

table, meaning it is the first message received for a given call attempt, the call is entered in the table and the message relayed to all adjacent nodes. If the call is found in the table, meaning it has been received and relayed previously, the message is ignored. This particular saturation algorithm thus precludes the possibility of the same message being sent twice from the same node.

Certain inherent merits of the saturation routing strategy make it especially attractive for a D&C network. They are:

- Elimination of any requirement for routing tables,
- Routing adapts instantaneously to the network configuration,
- Routing tends to favor the shortest and least used circuits,
- Subscribers may retain their directory numbers wherever they move and require no geographic numbering plans.

Several models are currently available in the Defense Department inventory which could be employed to assist in the development of an optimally configured network for D&C communications. Three models developed by the Defense Communications Agency for the AUTOVON and MEECN* appear particularly applicable. The "Minimum Cost Network Design Algorithm," "Network Performance Algorithm" and "Survivability Assessment Algorithm," already extant and operational as large-scale computer models within the Defense Communications Agency, are available for use by the DCPA.

It may be concluded that a D&C network can improve both survivability and performance through the application of switching and alternate message routing. In comparison with the current D&C communications networks, the "distributed" structure represents a significant departure

*MEECN: Minimum Essential Emergency Communications Network.

in switching philosophy. A moderately redundant network configuration will be more survivable, even with relatively unreliable or non-survivable links, and such a configuration is consistent with providing improved network performance at the lowest cost.

An adaptive saturation routing strategy, wherein messages are relayed to all adjacent nodes, is advocated to further enhance network survivability and performance. Such a strategy avoids the vulnerability inherent in centralized control, automatically adapts to changes in network connectivity, and easily accommodates mobile subscribers.

3.7 Meteor Scatter Burst Communications

Every day billions of sand-size meteors enter the earth's atmosphere and, upon burning, form long trails of ionized particles. These columns diffuse rapidly and usually disappear within a few seconds. However, during their brief existence, these ionized trails will reflect radio signals. By using successive meteor trails, radio communications can be effected by forwarding stored data at very high speed during brief bursts corresponding to the lifetimes of the individual meteor trails.

Because radiowaves hitting upon a meteor trail are reflected primarily in the direction for which the angle of incidence equals the angle of reflection, only those trails suitably oriented may be used for point-to-point telecommunications. As a consequence, bursts of traffic can normally be transmitted only about five percent of the time. Nevertheless, the bandwidth of the meteor scatter channel appears to be sufficiently large (about 100 kHz), to support fairly high average data transmission rates in spite of the low duty cycle.

The basic components of a meteor-burst communications system are shown in Figure 11. Equipment at both terminals is identical (except for the operating frequencies of the transmitters and receivers, which are interchanged across the path) and consists of: transmitter, receiver, throughput control unit, gated transmitting store, receiving store, and antenna system.

The transmitter radiates continuously on separate frequencies in the range 30-70 MHz, a typical separation being 2 MHz. Transmission quality, monitored at the distant receiver and returned via the return channel, is used by the control unit to adaptively administer data transmission. Messages are transmitted only when the transmission quality exceeds a prescribed threshold of acceptability. At the receiver, data is buffered in the receiving store and then discharged at conventional data rates to terminal equipment.

Operationally, the burst-like character of the communications equipment is not noted by the subscribers. Information flows into the transmitting store at one terminal and out of the receiving store at the other at a constant rate.

Meteor burst communications systems have several merits:

- The altitude of the reflecting meteor trails permits direct point-to-point communication over distances of up to 1500 kilometers.
- In a nuclear environment the propagation mechanism appears to be survivable although some additional attenuation due to absorption in the lower atmosphere should be anticipated.
- Low probability of intercept and antijam capability are inherent due to the directional character of the specular meteor trail reflections.

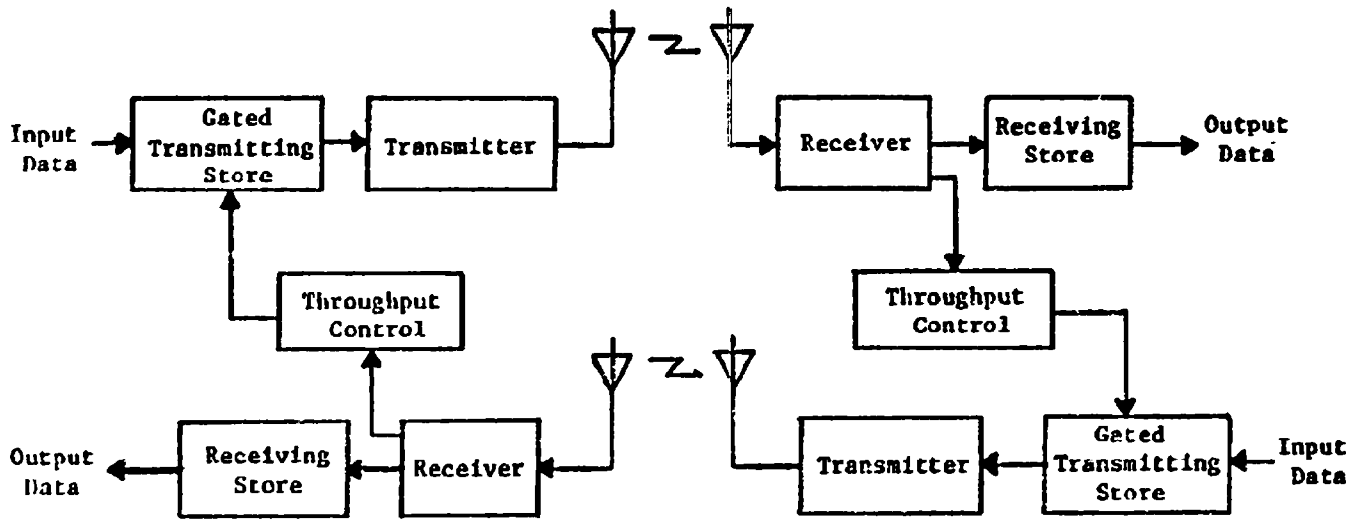


FIGURE 11
METEOR SCATTER COMMUNICATION SYSTEM

The received signal depends not only upon the number of meteor trails, but upon their orientation and position relative to the transmission path. This, in turn, depends upon the manner by which meteors are swept up by the forward motion of the earth as it revolves about the sun which leads to both diurnal and seasonal variations in system performance. On the morning side of the earth, meteors are swept up by the earth as it revolves about the sun. On the evening side, the only meteors reaching the earth are those which overtake it. This results in a maximum meteoric occurrence rate around 5 a.m. and a minimum meteoric occurrence rate around 6 p.m. A seasonal variation is introduced because the meteors are not distributed uniformly along the earth's orbit but are concentrated so as to produce a maximum incidence of meteors in July and a minimum in February. A further minor seasonal variation is introduced because of the tilt of the earth's axis relative to the ecliptic plane.

If meteor trails are to be used effectively for communications it is necessary to operate the transmitter in a burst mode, taking advantage of the relatively large signals which occur when suitable meteor trails are present and shutting down the system when they are not. The burst type of operation requires not only the detection of meteor trails, but the subsequent selection of trails which are suitable for the transmission of information.

One means of accomplishing the detection and selection functions simultaneously is to employ a transmitter and receiver at each terminal with the transmitters radiating carrier continuously. The carrier level is monitored in a narrow band at the receiver and, when the carrier exceeds a prescribed threshold level to ensure an acceptable signal-to-noise ratio, the presence of a suitable trail in indicated. A return control channel then releases the information from transmitter storage to the modulator for transmission at high speed during the

lifetime of the trail. The return channel may be used for control only or may also be used for point-to-point traffic in the opposite direction.

Meteor scatter communication systems are characterized by the discrete nature of the transmission medium and the requirement for control of message transmissions. Although analog storage services are available, (e.g., magnetic tape, tapped delay lines, surface-acoustic-wave (SAW) devices), the large delay and rapid readout capability required by meteor scatter communications is best carried out with digital storage. Further, as a consequence of the potentially large time intervals between transmission bursts (up to several seconds), meteor scatter appears inappropriate for real-time, duplex telephony. The bandwidth of the medium (about 100 kHz) is probably not enough for transmission of standard television signals. As a consequence, most if not all of the potential traffic will be digital data.

The character of the meteor scatter channel appears to place few restrictions on the choice of a digital modulation method. As a consequence, methods may include techniques such as Quadrature Amplitude Modulation (QAM). Several modulation methods are summarized in Table I where their capabilities are compared, using the same transmission bandwidth. Of particular interest is the eight-phase phase-shift-keying (8Ø-PSK) system, which will permit voiceband data transmission at an average rate of 4800 bps. This rate is also the maximum rate available within the Direct Distance Dialing (DDD) telephone system for unconditioned lines. Commercial facsimile terminals are presently available which also operate at this data rate.

TABLE I

COMPARISON OF DIGITAL MODULATION TECHNIQUES

Modulation	Band-width	Channel Bandwidth = 100kHz		BER = 10^{-6}
		Instantaneous Data Rate (R)	Average* Data Rate ($\bar{R}$)	Energy-Contrast Ratio (E_b/N_o)
BPSK	2R	50 kbps	2.5 kbps	10.6 dB
QPSK	R	100 kbps	5.0 kbps	10.6 dB
8Ø-PSK	2/3R	150 kbps	7.5 kbps	14.2 dB
16Ø-PSK	1/2R	200 kbps	10.0 kbps	18.8 dB
BFSK	3R	33 kbps	1.67 kbps	14.2 dB
QFSK	3R	33 kbps	1.67 kbps	11.3 dB
8-ary FSK	4R	25 kbps	1.25 kbps	9.7 dB
PR3-FM	2R	50 kbps	2.5 kbps	16.7 dB
PR7-FM	R	100 kbps	5.0 kbps	20.5 dB
PR3-QAM	R	100 kbps	5.0 kbps	16.7 dB
PR7-QAM	1/2R	200 kbps	10.0 kbps	20.5 dB

*Assumes a duty cycle of 5 percent.

The most important effects upon a meteor scatter burst communication system following a nuclear detonation arise as a result of excessive D-region* absorption. The amount of D-region absorption experienced by the meteor-scattered radiowave depends upon its frequency and upon the altitude and yield of the detonation.

The results of simulations developed by the Naval Ocean Systems Center indicate that all meteor scattered signals would be severely attenuated immediately following a nuclear detonation. For a low altitude burst, an operating frequency of 50 MHz might recover after experiencing only a few hours of blackout; an operating frequency of 150 MHz might recover in less than one hour. For the high altitude burst, a somewhat larger recovery period can be expected. In neither case, however, is the outage period due to a single nuclear burst expected to exceed six hours.

Current technology appears capable of creating a meteor scatter communications system that would have average data transmission rates twice as high as those used by previously deployed meteor scatter systems. This gain in performance is predicated upon three factors: (1) the meteor scatter channel is inherently capable of supporting instantaneous data transmission rates of 100,000 bits, per second,**

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*D-region: one of four layers of the ionosphere; when it exists, it occupies an area between 50 and 90 km above the earth.

**K. Folkestad, Ionospheric Radio Communications, p. 206: "In designing meteor-scatter circuits it should be recognized that the channel is capable of supporting very high instantaneous signaling rates. For instance, at (the Defense Research Telecommunications Establishment in Canada), tests have been conducted at 104 MHz with data rates up to 100,000 bits/s over a 1400 km path.

G. F. Montgomery and G. R. Sugar, "The Utility of Meteor Bursts for Intermittent Radio Communication," Proc. IRE, Vol. 45, pg. 1684: "Transmission experiments in a 100-kc band have not realized the theoretical capacity of the signal, mostly because of multipath propagation. About half the meteor bursts observed are unaffected by this distortion, however, so that a useful system of this bandwidth may yet be possible."

(2) adaptively steered antenna beams can be employed to isolate suitable meteor trails and thereby reduce transmitter power requirements by providing increased directive gain, and (3) transmitters can be operated intermittently thereby reducing average power requirements.

The application of meteor-burst communications for national needs is being studied by using the same equipment complement as employed in the Soil Conservation Agency's SNOTEL system (2 KW transmitter, 2 kbps data rate, binary PSK) but with an omni-directional aircraft antenna. The DCA will in November 1979 conduct an experiment to determine the feasibility of employing meteor bursts to provide a Minimum Essential Emergency Communications Network (MEECN) to effect survivable communications between the ground and airplanes.*

3.8 Spread/Spectrum/SCULPT Concepts

Spread spectrum communications are characterized by a transmitted signal which has a bandwidth much wider than the information bandwidth of the signal. Spreading the signal power over a wider bandwidth results in low signal power spectral density per system user. The same bandwidth may be used by many users simultaneously. The main process of a spread spectrum system is to spread a signal over the "common" bandwidth and then (at the receiving terminal), to separate it from other users without errors and with a minimum of interference between users.

In conventional spread spectrum systems, separation of the various signals is done by frequency division, where each user is assigned a portion of the spectrum either exclusively or to share with others. This sharing of the spectrum requires a network discipline to facilitate

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*J. L. Hentage et al., "Meteor Burst Communications in Minimum Essential Emergency Communications Network (MEECN)," Naval Ocean System Center Technical Report 138 (August 1977).

the efficient access of users to the communications channels. The separation is accomplished by assigning codes to various users, whereby each user's code functions as an address. Only the addressee can recover the information addressed to him.

By making the transmission bandwidth much larger than the information bandwidth, a high processing gain is achieved which enables the recovery of faint signals. This has proved to be desirable in the case of satellite communications, for deep space applications and for the detection of signals in an environment with high levels of interference.

Recent technological advances make spread spectrum technology even more desirable. For example, the advent of the charge coupled device makes it possible to sort out the users rapidly. This, coupled with expected increases in demand for communications by numerous users, has increased interest in spread spectrum techniques. The latter would make it possible for a communications system to accommodate many more users on a random access basis without a centralized network control. However, the relative bandwidth utilization efficiency between spread spectrum systems and other conventional narrowband systems requires further study.

There are two main types of spread spectrum techniques in use: pseudorandom noise code sequences and frequency hopping. Hybrids of the two techniques have also been used. The following paragraphs discuss these techniques.

The pseudorandom noise spread spectrum uses a pseudorandom noise (PN) sequence of binary digits (of one and zeros) with statistical properties that resemble those of thermal noise. Data and synchronization information are added to the PN sequence to form the PN code

and to enable acquisition at the receiver side. The resulting bit stream modulates a carrier frequency which is then amplified and transmitted. (A block diagram description of such a PN system transmitter is shown in Figure 12.)

At the receiving end, a replica of the code is correlated with the received code. This can be done in two methods: the first method requires the local PN generator to step forward or backward in the time relative to the received code until both codes are in phase. The second method requires the receiver to have a filter matched to the code. Matched filtering maximizes the signal-to-noise ratio at the output of the filter. The impulse response of the code-matched filter is a delayed replica of the input signal. The introduction of charge coupled devices (CCD) makes the use of tapped delay lines for matched filtering economically feasible. A spread spectrum system with a receiver using CCDs is currently being developed by The MITRE Corporation for the Maritime Administration. This system is designed to accommodate low power satellite communication users; hence, its name: Satellite Communications Using Low Power Technique (SCULPT). Figure 13 shows a block diagram of the SCULPT receiver.

A PN spread spectrum system is relatively insensitive to electromagnetic interference as shown in Figure 14. Such interference would be spread over the bandwidth of the PN signal and only a very small portion of the interference power spectral density will fall within the narrow bandwidth of the baseband signal after collapsing the spread spectrum.

Frequency hopping is basically frequency shift keying where the number of frequencies used is greatly expanded and where the frequencies are selected according to some pre-specified code. Thus, the available bandwidth is channelized into contiguous slots. At the transmitting

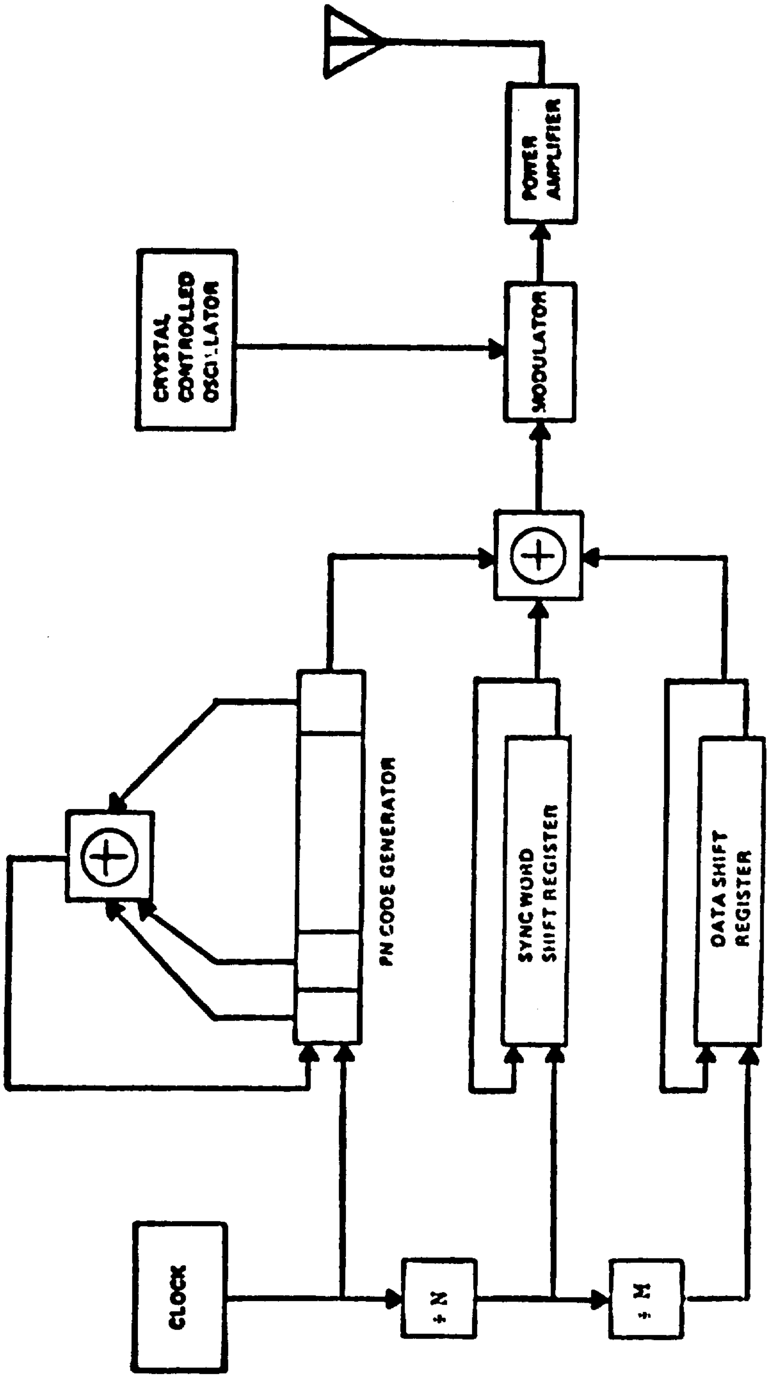

FIGURE 12
PN SYSTEM TRANSMITTER BLOCK DIAGRAM

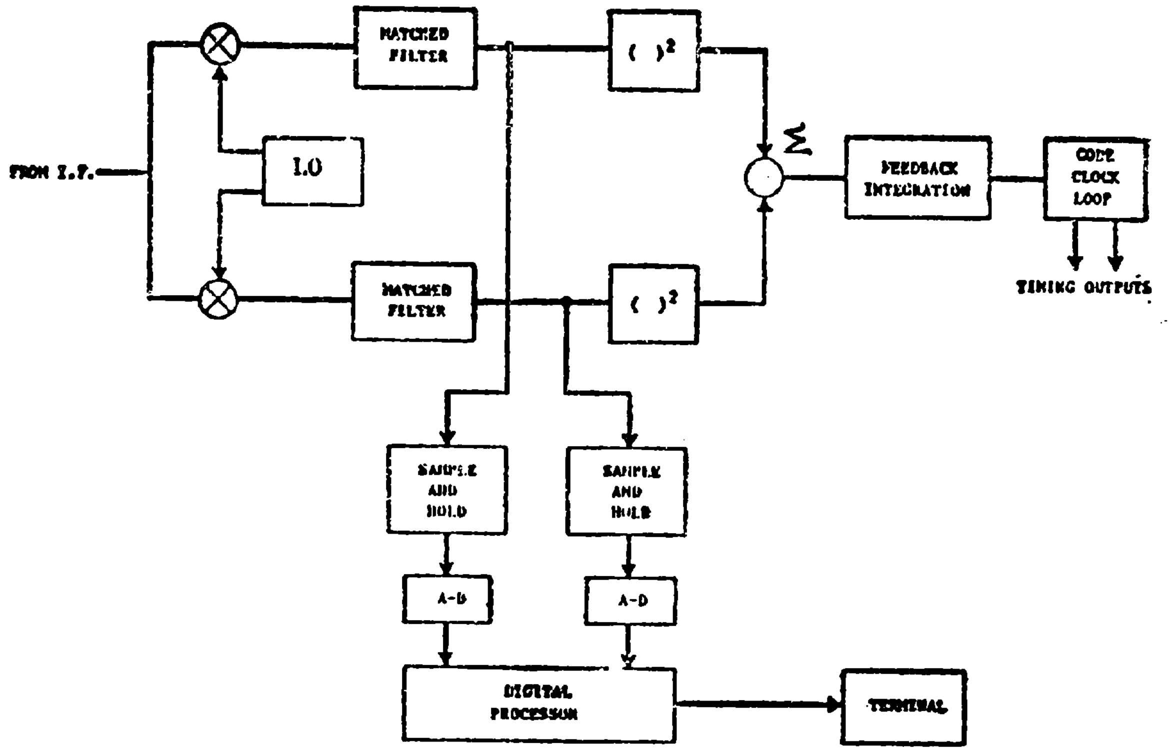

FIGURE 13
SCULPT RECEIVER

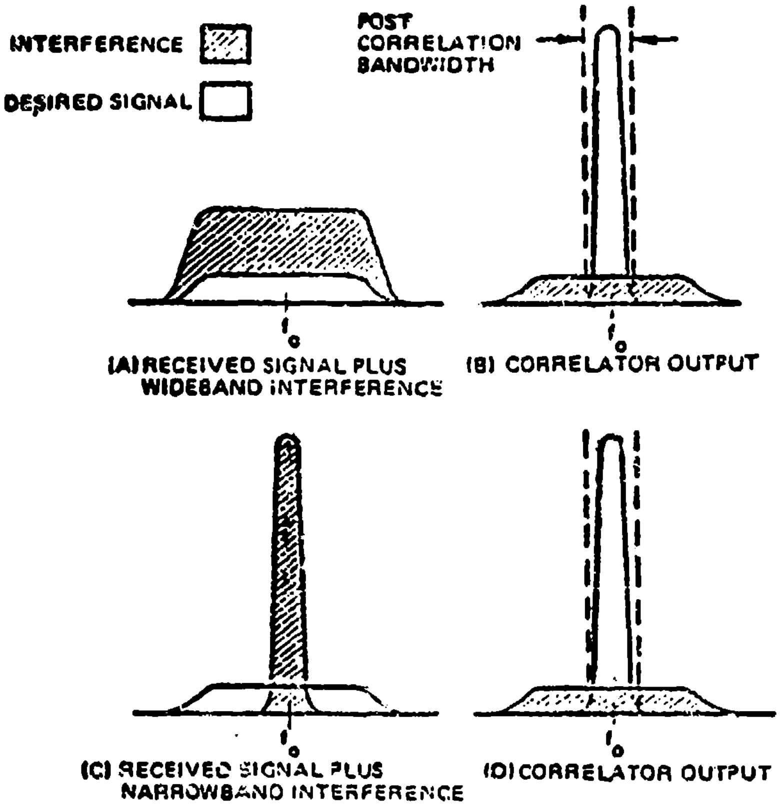

FIGURE 14
SPREAD SPECTRUM CORRELATION PROCESS

end, a digital frequency synthesizer is used together with a PN code generator for frequency selection. The input information is modulated on the carrier frequency prior to mixing it with the output of the synthesizer. At the receiving end another frequency synthesizer and a code generator to drive it are also required. The information is demodulated from the incoming signal after the latter is "dehopped" through proper synchronization of frequency and code. The code used must be a replica of the received code.

The separation between frequencies is chosen to be uniform and at least as wide as the information bandwidth to be modulated on the individual (channel) frequency. The RF bandwidth is determined by the product of the number of frequencies "n" of the synthesizer and the separation between the two contiguous frequencies, Δf. The processing gain of this spread spectrum system is then equal to the number of channels used.

One of the D&C communications requirements is the transmission of information such as sensor measurement of fallout radiation or other selected measurements from a number of diverse locations. Sensors would probably produce information which could be transmitted at a low data rate using low power, and possibly with a low duty cycle, i.e., once every minute or even less frequently. The sensor information would be fed to a central facility where the fallout situation is being monitored. A feasible mechanism for the relay of such information would be a satellite communications system.

The SCULPT spread spectrum satellite communication system could provide a viable medium for the transmission of critical information

under adverse scintillation and ionization conditions. The low data rate, the low transmitter power, and the fact that fallout sensors may be unattended, all match the SCULPT concept currently being developed. Furthermore, depending on bandwidth, thousands of transmitters could be accommodated by the satellite. Figure 15 is an overview of such a system. Each transmitter could transmit a signal of about 10W of power, which is relayed through a satellite with about 27 dB gain to a ground station having an antenna with a gain of about 50 dB. Such satellite transponders and earth stations are commercially available.

The use of a low data rate in this system is particularly suitable to alleviate effects of fading expected after a nuclear attack. The simple nature of the SCULPT transmitter combined with a more complex receiver makes it particularly suitable to the sensor application, since the information gathering system at a central civil defense facility could accommodate the SCULPT receiver.

In summary, systems such as SCULPT offer a desirable multiple access communications capability for information reporting after a nuclear attack. Such systems offer privacy of communications, an anti-jam capability, and the ability to accommodate various users with different data rates, all using the same bandwidth either simultaneously or alternately at random and without a network discipline. The random access capability coupled with a low duty cycle could result in a capability to accommodate a large number of users. Tests of this system concept are necessary, however, especially in an environment similar to that expected.

3.9 The Joint Tactical Information Distribution System (JTIDS)

The Joint Tactical Information Distribution System, JTIDS, is an evolving system designed to offer improvements in military

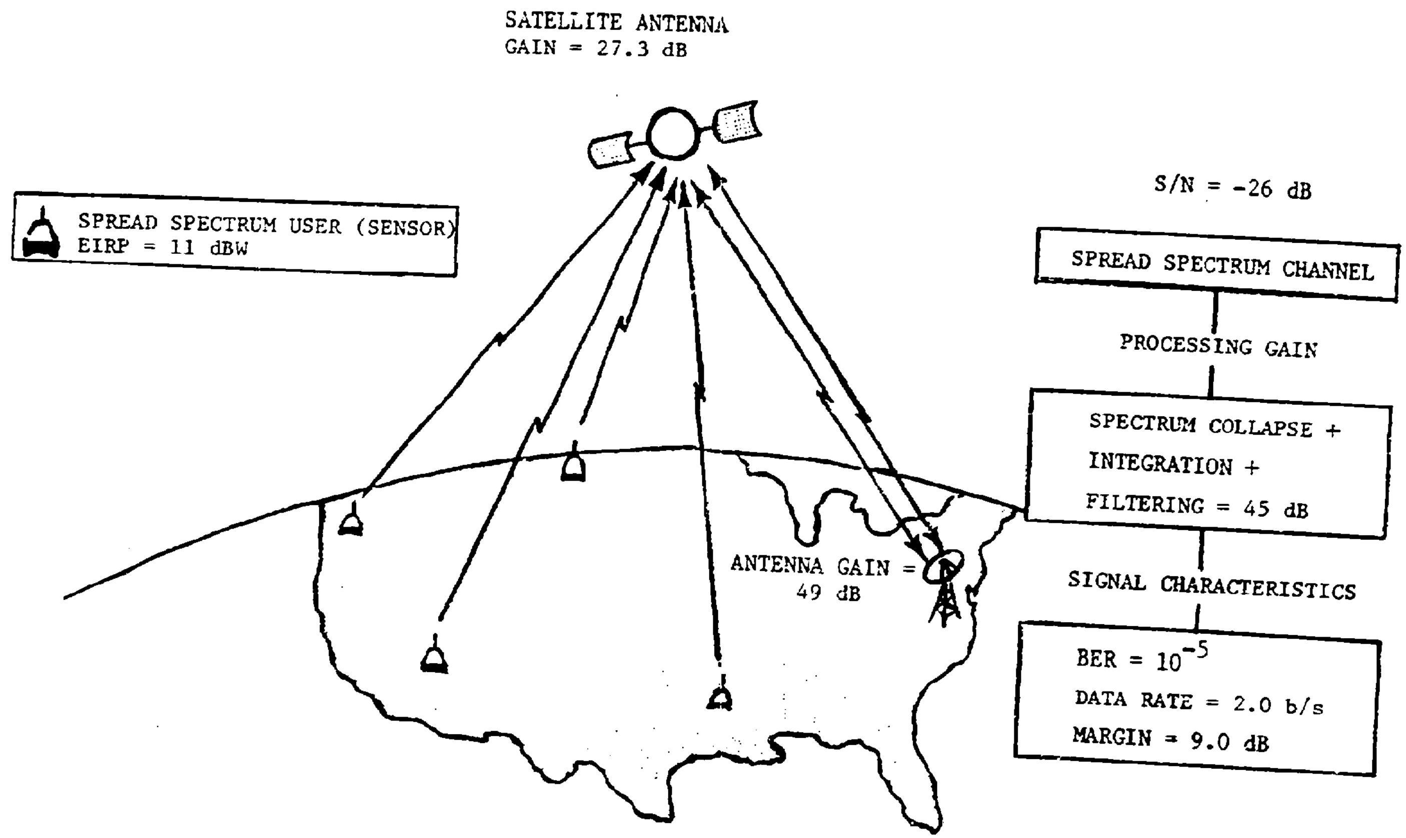

FIGURE 15
DCPA SPREAD SPECTRUM SENSOR COMMUNICATION SYSTEM

communications. Since JTIDS has the technological potential for providing secure, jam-protected digital communications, it is appropriate to consider JTIDS in the D&C role.

JTIDS is essentially a node-less information distribution network within which a community of JTIDS-equipped users can share a common pool of information. Information is reported digitally in pre-assigned time slots by all participating elements on a common broadcast frequency in the form of brief messages and is selectively accessed by each element according to its needs.

The JTIDS information net acts as a high-capacity, receiver-oriented tactical information distribution system. Participants who have information useful for direction, control, or execution broadcast that information routinely into the net, without needing to know who the recipient of the information may be, and the elements needing information extract it from that available on the net, without needing to know who furnished it.

"Receiver-oriented" means that, instead of having to issue a request for information to a specific party, the user can decide on a category of data he wants, query the net for data in the category, and receive anything the system contains on the subject.

Information on the net is refreshed at rates commensurate with the rate of decay of each class of information. When the receiver calls up a display of the desired information, all other system data is excluded by the same commands. Thus, selective retrieval is fundamental to receiver orientation and is a driving characteristic of the JTIDS architecture.

The information net's connectivity depends on omnidirectional antennas which reach all JTIDS-equipped elements in the net which are within line-of-sight. Coverage beyond line-of-sight ranges can be provided by relays, preferably airborne. Any JTIDS terminal can perform as a relay.

Any member of the net may be designated to act as the master station to serve as the system time reference to which all other members are synchronized. The master station requires no special timing accuracy or terminal features. Additional members can be added to the net as the situation develops; in the event of a station failure or destruction, the loss is confined to loss of that particular element's information or capability without crippling the net. The system can survive even widespread failure and still be available for use by the remaining terminals.

JTIDS has no dedicated switching centers or landlines. No fixed communications plant is needed. The system consists wholly of deployed terminals; to operate within it, each element requires only a JTIDS terminal. With appropriate interface devices, JTIDS will accept the inputs from a variety of communications equipment, routing them to their destinations where they will be read without the change in communications techniques being apparent.

A JTIDS net is organized on the principle of time division. Various elements are assigned specific time slots on the net within which to report information of general concern to the elements of the net. Condensed within a brief message format is a series of reports which communicate the information the element has to contribute; each element may report at a different rate depending on the mission, the frequency of the need to update, the quantity and criticality of the information and the nature of its roles.

The basic JTIDS timing structure, the epoch, is defined as 12.8 minutes; this is the period of time after which the time slots are renumbered. Active participants must have at least one time slot in each epoch. However, the value of some information decays much more rapidly than every 12.8 minutes, or even in some cases, every 12 seconds. If all members of the net were devoted to reporting every 30 seconds, the net would support 3,840 separate pieces of information. If the entire net were assigned to report every second, the number of participants in the net could be 128. These values give some idea of the reciprocal relationship between system capacity and mission demands.

An individual time slot is 7.8125 milliseconds long. The number of time slots assigned to each participant is based on that particpant's operational function and the amount of information he has to contribute. Again, the tradeoff is apparent. The less real time the requirements are, the more individual pieces of information the system can contain; the more real time they are, the fewer separate pieces of information. Vital pieces of information must be repeated at least one each epoch to remain in the net.

Time slots can be assigned either singly or periodically at a selected rate within each epoch.

The JTIDS is designed to support two types of messages: formatted and unformatted. Formatted messages are those in which each bit has a specific meaning and a large amount of information can be condensed into the brief message period. Formatted message transmission is preferred for this reason.

Unformatted messages are used for any data that does not fit the standard message formats. They may be longer or shorter than

the standard messages or they may simply be a continuous bit stream as in the case of digital voice.

Digitized voice information is taken from a processor which separates the bit stream into message-length packets of 225 or 450 bits for transmission. When the user transmits, his terminal processes the digitized stream from his voice processor and transmits those bits in every twelfth time slot for as long as he transmits. In the remaining 11 of every 12 time slots, the JTIDS terminal will be processing the digital messages carrying other information.

Speech is not an efficient method of information transfer. The time required to transmit a given message digitally compared to voice is on the order of 1:5000, hence there is a strong argument against the use of JTIDS for voice radio communications.

Since JTIDS operates at microwave frequencies, direct communications are confined to line-of-sight. However, the system provides the capability to relay to extend communications coverage to subscribers beyond line-of-sight. The relay function is based upon the principle of time-slot-delay relaying. A message detected in a particular time slot is decoded and a bit is set into the message indicating the message is being relayed. The message is retransmitted, usually within three to six time slots after reception. Any terminal receiving a message both directly and via the relay will process only one.

Any JTIDS terminal can function as a relay in addition to performing all its other terminal functions. Any number of terminals can operate simultaneously as relays, each assigned unique time slots for this purpose. When relays must be used, the total system capacity is cut. For every message relayed, an additional time slot

is used for single relay; building a chain of relays requires a chain of time slots. If all messages require relaying, system capacity is cut in half.

Four communications modes are being developed for JTIDS; they give the user the choice of operating in narrowband or wideband; secure or nonsecure fashion. Mode 1 secures the data and the signal structure and provides maximum jam-resistance by spreading transmission through both pseudonoise and frequency hopping techniques over the frequency range between 965 and 1215 MHz. Mode 2 does not use frequency hopping and the total bandwidth is 10 MHz. Mode 3 uses an identical synchronization preamble code for all time slots, and in Mode 4, neither the signal structure nor the message is encrypted. In Mode 1, up to 128 multiple nets can be created as needed in a geographical area, limited only by the self-jamming created when large numbers of nets are used in the same locality.

The JTIDS architecture requires that all elements transmitting on any net be time-synchronized with high accuracy, using as reference whatever station is acting as master at the moment. If any terminal transmits at the wrong time, the signals it sends out may not have time to propagate out of the environment before the next transmitter is scheduled to send, and at least some terminals in the environment may still be receiving the errant station's signal when the transmissions from the following transmitter are arriving. Under such conditions, messages sent in some time slots might not be received. Transmission timing error can have serious consequences to system connectivity.

To stabilize system timing, any one of the participating terminals may be designated the time master. The master terminal needs no special attributes; it simply does not adjust its time as all others

do, but merely identifies itself as master periodically. Other terminals in the environment weigh the master time more heavily than signals from other terminals, confirming synchronization.

3.10 Packet Radio

Another alternative for data transmission is packet radio. Packet radio is a two-way radio device that is used for dialog with a computer, transmitting data in short bursts rather than continuously as in voice transmissions.

Since a packet radio transmits only brief bursts of traffic, a relatively small source of power is required and small, portable transmitters are practicable. Such transmitters could communicate worldwide using satellite relays between individuals, computers, data bases, and possibly even machines.

A typical packet radio network is shown in Figure 16. The three primary elements of a packet radio network are the terminals, stations, and repeaters, any of which may be fixed plant or mobile installations. The terminals may be handheld devices, teletype-like devices, displays, computers, or sensors. The stations have overall responsibility for starting the network operations, routing, traffic control and directory services, and may also provide access to other networks. Repeaters serve to extend the network geographically.

Each terminal connects into the network via a radio/digital unit. The packet digital unit forms network traffic into discrete digital segments (packets) which are transmitted through the network by the packet radios over a common radio frequency channel at either 100 or 400 kilobits per second. A generalized network scheme consists of a terminal passing a message to the packet radio at 100 kbps; the packet radios transmit through the network at 400 kbps until the

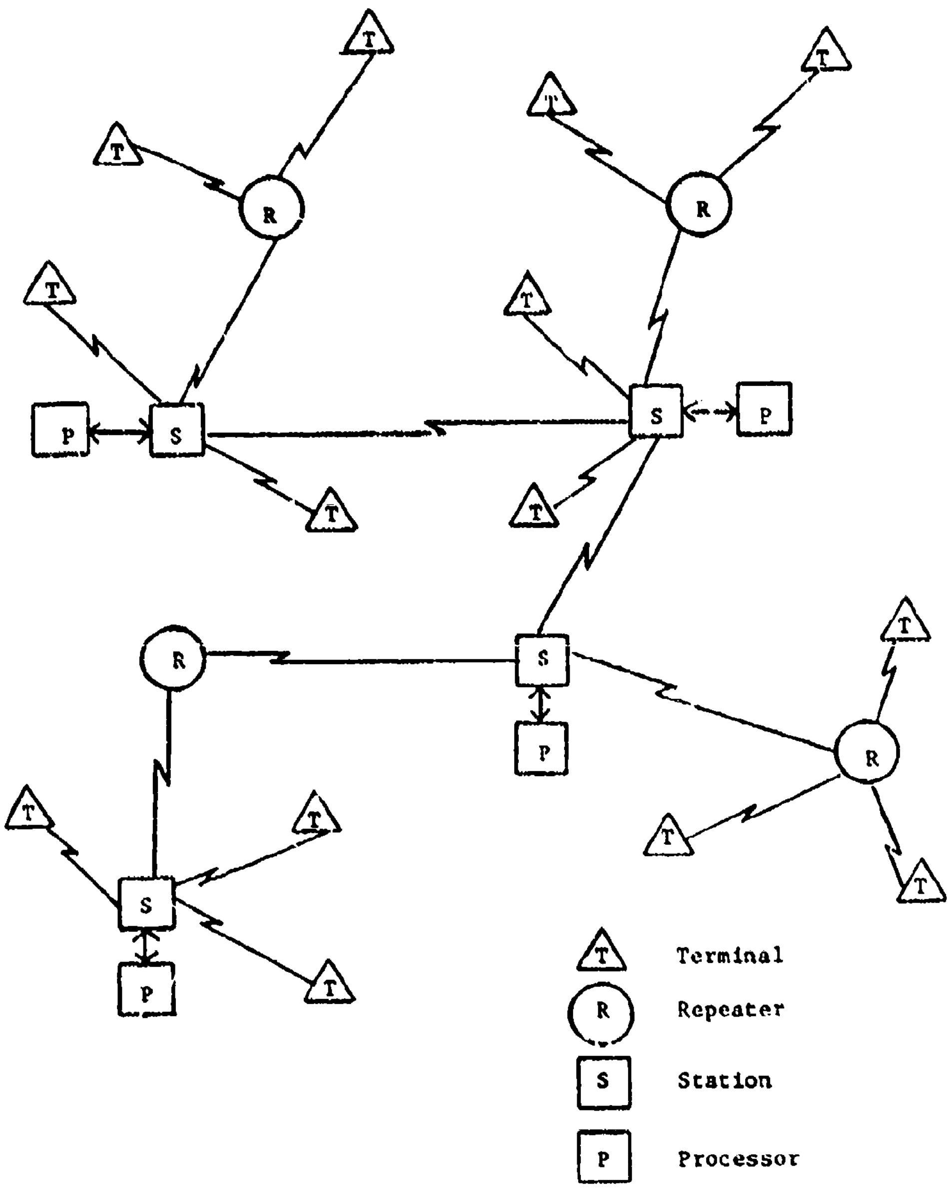

FIGURE 16
PACKET RADIO NETWORK

message reaches the destination radio which in turn transmits it to the addressee terminal at 100 kbps.

The radio frequency, signal processing, and digital functions are all contained in the packet radio. The radio and digital functions may be housed in the same cabinet or in separate cabinets.

The radio unit accomplishes the analog signal processing and the digital unit performs the digital processing. The units may be separated up to 300 meters, allowing the digital unit to be located close to the host processor, computer or terminals, and the radio unit where transmission is optimized, such as on a pole. The antenna is typically a set of stacked dipoles which provide about 10 dB omnidirectional gain.

Terminals, stations, and packet radios communicate by packets of digital information varying in length from 10 to 132 (16-bit) words. The first three words are a preamble used for packet synchronization and the last two words are used for a 32-bit checksum. The packet radio automatically generates the preamble and the error checksum. A packet header, which uniquely identifies each packet, consists of 10 words and follows the preamble. The data or text of the message comprise the remainder of the packet.

The header of each packet contains an indication of length of the packet, the source and destination, sequence number, its routing and information on the type and disposition of the packet. This information is used to route, process, and forward the packet through the network. As the packet travels through the network, the packet radio receiving the packet transmits it and waits until other packet radios receiving the packet retransmit it. When any of the retransmitting radios sends the packet back to the initial radio it is considered an "echo acknowledge."

When the packet arrives at its destination, the destination packet radio passes the packet to the terminal or station and returns a positive acknowledgement for receipt to the source packet radio if it has been requested. If the source packet radio does not receive acknowledgement of receipt after a predetermined number of retransmissions, the terminal or station connected to the radio will regenerate the message.

In establishing communications, the packet radio software periodically generates search packets toward a station. The station analyzes the search packets and assigns a hierarchy level to the packet radio based on an optimization criterion, such as minimum hops.

After this is completed, the packet radio is ready to receive and transmit data. Packets are transmitted on a first-in/first-out basis as they are generated and received by the packet radio. Depending on the packet type, a packet may be transmitted once only or the packet may be retransmitted until an echo acknowledge is received.

Packet radio needs a form of multiple access control which permits many scattered transmitters to transmit on the same channel at the same time. A simple form of control called the ALOHA control, which has been applied to both satellite and terrestrial links, has been employed in Hawaii.

ALOHA is a simple contention scheme. Each terminal is attached to a transmission control unit with a transmitter and receiver. The control unit accepts the message and forms the packets which include the header and error detection code. After assembling the packet, the control unit transmits the packet at random and all devices receiving the transmission frequency receive the packet. The packet

is ignored by all receivers except those to which the packet is addressed, which returns an acknowledgement.

Since the transmissions from each terminal packet radio are transmitted randomly, they can "collide." When this happens, the error codes indicate the collision and no acknowledgement is transmitted. The terminal packet radios then automatically retransmit their packets, this time hopefully without interference. To help overcome collision of packets on the retransmission, the ALOHA scheme provides a randomized time interval before retransmission.

Because with increased channel use, the traffic attempting to use the channel builds up at an increasing rate, it can be shown that the maximum use of a classical ALOHA channel is 18.4 percent. A chain reaction develops with the retransmitted packets themselves causing retransmissions so that above a certain level of traffic the channel becomes unstable. There are ways of mitigating the low channel utilization: these methods are known as "slotted" ALOHA, carrier sense, and FM discrimination. A combination of these techniques can provide channel use as high as typical landline systems.

In "slotted" ALOHA, packets begin transmission at a specific time interval instead of randomly. The time for the transmission is determined by a system-wide clock, with each transmitter synchronized to the clock. This scheme has the advantage of reducing the number collisions to half, however, all packets must be of equal length. The maximum theoretical use of a slotted ALOHA channel is 36.8 percent.

Other possibilities include use of a reservation protocol which permits reservation of certain time slots, and by use of an early

warning system which divides terminals up by priority. High priority terminals send out a signal before they transmit; all radios hear the warning signal and avoid the high priority time slot.

A simpler early warning system is the carrier sense mechanism. Carrier sense implies that a terminal can detect when another is transmitting by detecting its carrier. If this is the case, the transmission will be slightly delayed to avoid a collision of packets. The most effective way to alert the terminals is for the central station to transmit a "busy signal" while it is receiving. The busy signal is transmitted on a narrow bandwidth control channel and all stations will receive it. When carriers sensing is used, as much as 80 percent of channel capacity can be used.

When FM modulation is used, the radio receiver is designed to discriminate between strong and weak signals; the weaker signals are rejected. In this scheme, the weaker signal is required to be retransmitted. If the power output of a transmitting packet radio could be adjusted, the probability of two colliding packets is low and the stronger signal will be received correctly. In theory, use of a slotted channel and FM modulation could use 100 percent of channel capacity. In practice this has not be achieved.

In summary, it can be seen that JTIDS and packet radio are similar in many ways. Both are methods of distributing data to a large number of users in a tactical arena. Both concepts are in a fluid stage of development and rapid changes can be expected, but both systems have hardware in various stages of development.

Both systems are line-of-sight systems, relying on relays for coverage beyond the horizon. The use of relays renders both systems vulnerable to physical damage but with little impact on overall network

survivability. Both systems use omnidirectional antennas to minimize set-up and mobility problems.

It is inappropriate to view JTIDS and packet radio as competing concepts. There has been a transfer of technology between the two systems capitalizing on the strong points and mitigating the shortcoming of both and this exchange probably will continue. By the time that the requirements for D&C communications are defined there may be relatively few differences in the two concepts and selection between the JTIDS and packet radio can be made at that time.

4.0 EVALUATION AND INITIAL DESIGN CONCEPTS

4.1 General

The evaluation of the current D&C communications system leading to a consideration of initial new designs is accomplished in the context of four "emergency condition situations" or phases that have been identified by DCPA.* The four conditions are:

- Crisis: The time period (for situation) where there is a threatening international development and the public expresses a desire to know of the nature of the crisis and how it affects them, or when the President needs to inform the public of the seriousness of the threat. A crisis extends to a period of attack warning or subsides if there is a lessening of the threat. (Program D-prime population relocation operations commence.)

- Warning: When Commander-in-Chief, NORAD, declares the country is under attack, or when an accidental launch warning is issued, and the public is directed to go to shelter. (Population relocation continues.)

- In-Shelter: The period of time from when the public enters shelter to the time they are directed to emerge because the radiological fallout hazard is evaluated as safe enough for emergence.

- Post-Attack Recovery: The period of time from when survivors emerge from shelter to the time when legitimate civil government effectively maintains law and order and the nation's economy can support all survivors and steady capital growth.

4.2 Evaluation of the Current D&C Communications System

It has been observed that the current communications support provided by CDNAVS, CDNATS, CDNARS, NAWAS, and the switched systems is adequate for peacetime requirements. However, under crisis conditions

*Defined in National Backbone System of Facilities for State and Local Government Direction and Control of Emergency Operations - A Concept Paper, review draft, DCPA, December 1975.

the current communications system is not expected to have the flexibility and responsiveness to support population relocation as envisioned by Program D-prime. Above the local level, the fixed-plant communications design provides little capability to support fluid population relocation operations and changes in the locations of civil defense activity and responsibility. The meager channel allocations from regional to state centers (see Figure 5), as well as from state to local units, are not expected to provide sufficient capacity under stress conditions. Above regional level, the availability of access to the switched systems (particularly AUTOVON and AUTODIN) may provide sufficient capacity if they are not pre-empted for military traffic. The same apparent deficiencies will persist during the transition to the in-shelter condition as population relocation continues and as other sectors of the population enter shelters.

During and immediately after a nuclear attack (during the in-shelter emergency condition and early post-attack recovery phase) the present D&C communications system will no doubt be seriously damaged and probably be out of service. This will be caused by damage to an expected large segment of the AT&T Long Lines network upon which the D&C communications system is presently dependent. Although many long line trunks will survive, the restoration of critical circuits (including those of DCPA) rely on what is presently a man-intensive process. Unfortunately, at persent there is no assurance that the personnel required will be available to restore the system; they too will be in-shelter.

Also the D&C communications system has only a limited capability to respond to changes in traffic demand and to possible realignment of D&C responsibilities. If a regional center is destroyed requiring

another to absorb its duties, a corresponding change in communications support would be difficult to provide. Even the HF radio net, CDNARS, is vulnerable to blast damage to antennas and interruptions in transmission caused by ionization of the atmosphere. The D&C communications system is therefore not responsive under conditions in which it is needed most.

In the post-attack recovery period, the existence of a D&C communications system depends on the extent of damage to the commercial plant, the availability of spare resources and the responsiveness of repair personnel. The CDNARS, the only technology independent of the AT&T Long Lines system, does not have the channel capacity to be the sole D&C communications capability during this phase. The responsiveness of the D&C communications system therefore will be very limited.

4.3 Initial Design Concepts

Typically, initial system design involves consideration of tradeoffs in performance, cost, technical risk and development time. Determination of these parameters was not a goal of this study and therefore a complete initial system design cannot be completed. In addition, the questions concerning the effect of implementation of the D-prime program and the formation of FEMA must be ascertained and considered in the final system design. It is possible, however to provide preliminary thoughts on the D&C system design.

It is felt that designs should be furnished for the near term (operational in 1980-81) and the long term (operational in 1985). For the immediate future, implementation of the distributed, switched

network and adaptive saturation routing strategies described in the section on network options can provide a relatively quick payoff in system responsiveness.

The key to survivability of the D&C communications system in the longer term is the employment of redundant modes of communications. The pervasive AT&T Long Lines should be the basis of the D&C system. More sophisticated network design options should be considered however. Redundant links on alternate routes and adaptive saturation routing must be carefully studied and provided. Digital transmission, switching and distribution should be used to benefit from the better signal regeneration capability, the ability to switch and multiplex voice, data and other type signals, higher transmission rates, and higher system capacity. In addition to this basic network, an independent satellite network should be implemented. This system could possibly be shared with some other critical service in order to justify the expected high cost. Millimeter wave satellite links, perhaps in the 100 GHz band, with TDMA and DAMA capabilities, should provide flexible and responsive support even in the fluid population relocation situation. Since system survivability is closely related to redundancy of communications resources, a third and final communications capability appears to be justified. Such a system would trade capacity for survivability and be similar to the military MEECN* system. For this purpose, a meteor burst scatter system seems to provide the requisite survivability, flexibility and responsiveness characteristics.

*MEECN: Minimum Essential Emergency Communications Network.

JTIDS or a Packet Radio System (or a derivative of the two) has potential for use between state and local civil defense elements and can serve well in support of population relocation operations. JTIDS/Packet Radio can be augmented at the state and local levels by residual communications resources such as police and other mobile radios and the surviving commercial plant. For information feedback and radiologic sensor information transmission, particularly during the in-shelter emergency condition, an automatic system such as SCULPT appears to have potential.

In summary, concept development and initial design of a D&C communications system for the next decade is, at this state, mostly speculative. It is apparent that the present D&C communications system is adequate as a peacetime system, but that it will have serious deficiencies before, during and after a nuclear holocaust. It is also clear that there is a shopping list of advanced communications technologies which will, at least, mitigate the problems associated with the nuclear weapon environment.

Many questions remain unanswered concerning future D&C communications system design:

- How will the merger of DCPA into FEMA affect the requirements for a D&C communications system?
- What will the communications topography be a decade from now, in terms of traffic originators and addressees, locations, organizational structure?
- What are the detailed operational scenarios for the design time period?
- What is the expected communications flow in terms of volume, frequency and type?
- What are the operational performance criteria for a D&C communications system?

- What is the full impact of Program D-prime on D&C communications?
- How well will the AT&T Long Lines network function, under adverse conditions?

These questions can be answered only by a system definition study, or architecture, for a survivable, flexible, responsive and supportable direction and control communications system. A system definition study is the natural follow-on to this preliminary overview of advanced technologies for a survivable D&C communications system.

APPENDIX

Digital Technology

Digital and PCM Communications

Information may be transmitted over a communications medium in two forms, analog or digital. Analog is the more traditional way to transmit a continuous range of frequencies, which vary as the input signal varies. Digital transmission is a stream of on/off pulses called bits that can be transmitted at an extremely high rate. Pulse code modulation (PCM) is a technique in which voice and other analog signals are converted into a stream of bits.

In order to convert an analog signal (such as voice) to a pulsed signal, the analog signal must be sampled at periodic intervals. The simplest form of sampling produces pulses with an amplitude proportional to the amplitude of the signal at the instant of sampling. This process is called pulse amplitude modulation, or PAM. Instead of transmitting an infinite number of amplitude values, it is normal to transmit only a limited number of discrete values, or to quantize the signal. In systems in actual use today, 128 pulse amplitude values are used. After quantizing, the value of the amplitude is coded into a binary pulse train. The process producing the binary pulse train is called pulse code modulation.

If the highest frequency of the signal is W hertz, it can be mathematically shown that a pulse train of 2W pulses per second is sufficient to carry it. Therefore, for a typical telephone call with a maximum frequency of 4000 hertz, a digital bit rate of 56,000 bits per second is needed (7 bits per sample). However, transmission facilities can carry two million bits per second and it is therefore worthwhile to multiplex several signals. Time-division multiplexing is generally used.

A major advantage of using digital techniques for transmission is the regenerative process. In analog transmission repeaters,

noise and distortion are amplified with the signal and, after several amplifications, the cumulative distortion and noise level becomes excessive. In digital transmission each repeater regenerates the digital signal, rendering it impervious to the distortion and noise in the medium.

PCM also has these advantages:

- Lower costs per telephone channel.
- Greater utilization of existing plant.
- Transmission is unaffected by fluctuations of the medium (within certain limits).
- All types of signals may be multiplexed without interference: voice, teletype, television, facsimile, computer data.
- Much higher transmission rates can be achieved.
- PCM is compatible with the newer transmission media, such as laser-pulsed optical fibers.
- Computerized satellite ground stations handling time-division multiplexed bit streams provide the most economical use of satellites.
- Digital transmission makes effective encryption easy to achieve.
- Time-division multiplexing provides advantageous switching methods in addition to transmission multiplexing.
- Concentiators, which are inexpensively built using digital techniques, can substantially reduce the cost of local distribution networks.

A disadvantage of digital transmission is that a much greater bandwidth is required. Because of signal reconstruction, however, digital transmissions can survive traveling over a channel with a

high level of distortion and with a poor noise-to-signal ratio. There is a tradeoff between bandwidth and the noise-to-signal ratio; a given transmission link can be operated at a higher bandwidth but distortion and the noise-to-signal ratio will be higher. A high bit rate (higher bandwidth) can be transmitted if the digital signal is reconstructed sufficiently often.

Much of the telecommunications plant in the United States is designed for analog transmission. To transmit data over analog facilities it is necessary to convert the digital signal into a signal within the voice frequency range. Modems used for this purpose are one of the following:

- Amplitude modulation, double sideband (DSB-AM)
- Amplitude modulation, vestigial sideband (VSB-AM)
- Frequency shift modulation (FSK)
- Phase shift modulation (PSK)

In DSB, binary states are represented by the presence or absence of an audio tone or carrier. In VSB unwanted sideband components are filtered out and as a result, the signal takes only about three-fourths of the bandwidth required for DSB.

FSK has nearly universal application for the transmission of digital signals at the lower data rates (1200 bps and below). In FSK, two binary states are represented by two different frequencies. FSK can show a 3 or 4 dB improvement over DSB and VSB in most types of noise environment. Another advantage is its immunity from the effects of non-selective level variations such as fading in high frequency radio transmissions.

For systems using higher digital rates, phase modulation becomes more attractive. Various forms are used such as two-phase, relative phase and quadrature phase. A two-phase system uses one phase of the carrier frequency for one binary state and the other phase for the other binary state. In the relative phase system, a binary "one" is represented by sending a signal burst of the same phase as that of the previous signal burst sent. A "zero" is of a phase opposite to the previous signal. The signals are demodulated by integrating and storing each signal bit burst and comparing it with the next signal burst.

In the quadrature phase system two binary channels are phase multiplexed on one tone by placing them in phase quadrature. An extension of this technique place two binary channels on each of several tones spaced across the voice channel. Phase modulation allows utilization of all available power for intelligence transmission and has a good noise rejection capability, but the complexity of the equipment is a disadvantage.

Higher level modulation schemes result in the achievement of necessary spectrum density at the expense of some loss of threshold performance. Today, the state-of-the-art in common carrier radios is 1344 voice channel, 90 Mbps systems using 8 phase PSK (8Ø PSK) modulation. A 4032 voice channel, 274 Mbps, 18GHz, system for short haul communications is also in use.

The advantages of digital and PCM communications to DCPA lie in the acceptance of this form of transmission commercially. The lower cost per channel, ease of multiplexing various types of transmissions, higher transmission rates and signal reconstitution characteristics provide an advantage in responsiveness and flexibility. Although a greater bandwidth is required, this characteristic is

acceptable to the higher-frequency transmissions of satellite systems and laser-fiberoptic systems. Where conventional narrowband transmission faculties must be used, signal compression techniques may be employed as discussed in the next section.

Signal Compression Technology

Digital channels are being introduced at a rapid rate. Commercial telephone companies are using PCM encoding of voice, with a requirement of 64,000 bps in each direction. Methods of encoding voice transmission into a much smaller number of bits are discussed in this section.

PCM sampling 8000 times per second reproduces any frequency up to 4000 Hz. However, most of the energy in speech is in frequencies below 1000 Hz and the signal does not change very rapidly. Fewer bits are needed per sample if, instead of the absolute value of the sample, the difference from the previous sample is encoded. This technique is called differential pulse code modulation, DPCM.

Signal differences are also encoded in a technique called delta modulation, using only one bit per sample. The one bit indicates whether the signal amplitude increases or decreases at the instant of sampling. The rate of change of the signal amplitude determines the number of pulses needed for this form of encoding. If the peak amplitudes are of low frequency and the high frequency components are of low amplitude (as in human voices) fewer bits are required. Delta modulation circuits are now in service which encode speech with good quality into 32,000 bits per second and this rate should drop to 16,000-24,000 in the very near future.

The quality of the transmitted voice can also be improved by increasing the number of sampling levels for the amplitude values

which occur most often, and decreasing the number of levels for amplitude values which occur least often. Small amplitude values of speech occur more often than large ones and therefore a scheme called companding increases the spacing of the quantizing levels for the stronger signal levels.

A <u>compandor</u> is a device that, in effect, compresses the higher-amplitude parts of a signal before modulation and expands them back to normal again after demodulation, thereby favoring the weaker parts of the sign ' and reducing quantizing error. Companding is used with PCM, differential PCM and delta modulation.

<u>Vocoders</u> are a class of encoders which try to produce semantic clarity without faithful voice quality. Vocoders transmit enough energy to synthesize voice without preserving the original voice waveform.

The channel vocoder is one form of vocoder. It sends three types of information: first, it sends information about pitch; second, the vocoder indicates when speech is "voiced" or "non-voiced" (when the vocal cords are in operation); third, the channel vocoder transmits information on frequencies other than the primary pitch. The speech is synthesized from this information. Two initial sound sources are used, a hiss generator and a generator of a buzzing sound consisting of pulses corresponding to the pitch of the vocal cords. The buzz is turned on during periods of voiced speech and the hiss during unvoiced speech. The hiss or buzz is then split into 16 channels, each of which is mo lated by the 16 frequency bands transmitted. The result is speech of high intelligibility but unnatural sound. This type of vocoder has been operated between 2400 and 4800 bps.

The newest technology of vocoders involves devices that use a hybrid of PCM transmission and channel vocoding. The low frequencies (200-1000 Hz) are transmitted complete in DPCM and the higher frequencies into bands as with a channel vocoder. The lower frequencies are then combined with the samples to synthesize the higher frequency speech. This system, called a voice-excited vocoder, typically uses 7200-9100 bps and gives better voice quality than the pitch-excited vocoder.

Linear-predictive coding is another promising technology. It extracts information from speech in the form of a digital pulse stream and then attempts to transmit the complete waveform instead of samples. Linear-predictive coding generates an error signal giving the difference between an actual pulse value and a predicted value based on previous samples. The linear-predictive coder extracts information on gain factor, pitch information, and voice-unvoiced information. Far fewer bits are required to transmit this information. Unlike frequency vocoders, linear-predictive vocoders encode speech more accurately when it changes fastest, and can therefore provide more natural-sounding speech using 10,000 bps or less.

DPCM and delta modulation may be used to encode video in the same way as voice. Differential video encoding employs a feedback loop and a slightly delayed signal which is subtracted from the input signal. When the subject is still, the incoming signal is constant and the difference signal is zero. For rapid movement, the difference signal is large. Tight differential coding can be overloaded when the image moves too fast, resulting in a blur across the screen.

TASI, Time Assignment Speech Interpolation, is a technology used on subocean cables for doubling their capacity by continually

reassigning the channels to the telephone speakers. On normal telephone calls, no one is speaking for about ten percent of the time; on four-wire or quad circuits, the path in one direction is used only about 45 percent of the time. TASI is designed to detect the caller's speech and assigns a channel in milliseconds after he begins to speak, at the loss of only an undetectable amount of the first syllable. The speaker retains the channel until he stops speaking, at which time it is allocated to another speaker.

The digital equivalent to TASI, <u>Digital Speech Interpolation</u>, <u>DSI</u>, is faster and more efficient than the older TASI. DSI has been used on satellite channels, more than doubling the capacity of the channels on which it is used.

<u>Switching</u>

Three components are needed to provide end-to-end communications: a trunking system, a local distribution network and a switching system. As described earlier, future trunking systems will be characterized by very high bit transmission rates using microwave radio circuits, coaxial cables, satellites, waveguides and even wire pairs capable of carrying the traffic of many users simultaneously using time-division multiplexing. Local distribution networks consist (and probably will continue to consist, in 1985) of wire pairs in a cable.

Switching between trunks and local loops and between trunks is the remaining component. The efficiency of the switching function is an important factor in data communications systems. In voice communication, a ten second switching time is acceptable but in data transmission where 4800 bits are transmitted per second, a 1/10 second delay is unacceptable.

There are two ways in which high speed switching can be performed: circuit switching and packet switching. Circuit-switching makes and breaks connections. Data is not stored at the switches and all switches must be correctly connected before the transmission is made. This process of switching must be done very quickly to be effective. Computers are used for this purpose and the fast-connect switches may not be electrical paths. Time-division switching, in which different messages are interleaved as they flow through the switch, may be used.

Packet switching is a form of store-and-forward switching. It is intended primarily for real-time machine-to-machine traffic including terminal-to-computer connections. A packet switched network delivers its packet in a fraction of a second and deletes the message from memory as soon as correct receipt is acknowledged.

The input computer is known as the "host" computer. When the host computer sends data, it passes the data with an address code to the local network computer where it is formatted into one or more packets. Each packet contains the control information to transmit the data correctly. The packets are transmitted from one computer to the other until it is received at the destination network computer where it .eformatted, reassembled and passed to the destination host computer.

The network control protocols executed in communicating host computers and the switch processors provide for flow and routing control, error detection and retransmission and the control necessary for buffering required to support store and forward operation of the network. Each switch provides for dynamic alternate routing as well as hop by hop acknowledgement.

Packet switching was developed by the Defense Advanced Research Projects Agency (DARPA) in the late 1960's and early 1970's and the ARPANET packet switched network has been in operation since then. ARPANET is the basis for AUTODIN II, the military **secured,** computer-communications network of the Defense Communications Agency for the early 1980's.

Packet-switched networks support data transmission but cannot support voice, video or facsimile transmission. To switch bandwidth in a time-varying manner between voice, data and other uses, requires a more flexible technique than packet switching, such as time-division switching.

Time-division switching is practical when time-division multiplexing is used, either of PCM signals or data. A feature of time-division switching is that it can handle streams of traffic of differing speeds. Most of the time-division switching equipment employed today switches fixed capacity channels, but even this is a quantum improvement over conventional switching.

The input to the network may be a PCM or digital transmission line. The signals are time-multiplexed by the switch onto a fast bus, and the resulting stream is demultiplexed at the destination by accurately timed gates. When the switch switches voice signals (not data) there is no need to completely digitize the voice; it may be left in PAM pulses. There are one eighth as many PAM pulses as in the completely digitized signal and therefore a higher throughput is possible.

PCM links, digital radio, waveguides and satellites make available high capacity channels which can be shared by time-division. If there are multiple access points and access is accomplished in a

digital time-division fashion, it is known as Time-Division Multiple-Access, or TDMA. (FDMA, Frequency-Division Multiple-Access, which is also used, implies separate frequencies for different users as in broadcasting. Time-division implies different time slots are allocated to different users).

Channels may also be assigned by allocation to users on demand. Demand-Assigned Multiple-Access (DAMA) TDMA has been used experimentally. Multiple access is essential for efficient use of satellites with many user locations. For example, ground stations are being produced with control mechanisms to permit many locations to share a satellite transponder on a demand basis. There are three ways of providing such a control function:

- Central control: A computer at a central control point accepts requests for channels, allocates them and informs the interested parties of the allocation.
- Decentralized control: Each station has its own form of control. Any station requiring channel space requests it over a common control-signalling channel with other stations hearing the request.
- Contention: A high-capacity channel is shared free-for-all. Short bursts of information are transmitted randomly; if they conflict, the information bursts are retransmitted.

One advantage of decentralized control is that the system is not vulnerable to the failure of one control station, but this arrangement is more costly. Centralized control is preferred when elaborate allocation schemes are required.

Burst modems are used in TDMA to transmit high-speed bursts of data. A burst can carry voice, video, data or any digitally encoded information. A station may transmit many voice channels or, for example, a video channel in which case the station is allocated

frequent bursts or large bursts. A burst from one station may contain information addressed to many other stations. Each station receives every burst but extracts only those addressed to it. It stores the items in a buffer and assembles all the bursts. The control of the bursts and the allocation of bursts to users resembles a computer operating system. Because the bursts can be of widely varying length, all types of signals can be carried. This technique is extremely flexible.

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